AFRL-HE-WP-TR-1999-0191

UNITED STATES AIR FORCE RESEARCH LABORATORY

THE CYBERLINK™ INTERFACE: DEVELOPMENT OF A HANDS-FREE CONTINUOUS/DISCRETE MULTI-CHANNEL COMPUTER INPUT DEVICE

Christian Berg
Andrew Junker
Aric Rothman
Ralph Leininger

BRAIN ACTUATED TECHNOLOGIES, INC.
139 EAST DAVIS STREET
YELLOW SPRINGS OH 45387

Grant McMillan

CREW SYSTEM INTERFACE DIVISION
HUMAN EFFECTIVENESS DIRECTORATE
WRIGHT-PATTERSON AFB OH 45433-7022

FEBRUARY 1999

FINAL REPORT FOR THE PERIOD 6 NOVEMBER 1996 TO 5 NOVEMBER 1998

Approved for public release; distribution is unlimited.

Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB OH 45433-7022

NOTICES

DISCLAIMER

This Technical Report is published as received and has
Not been edited by the Air Force Research Laboratory,
Human Effectiveness Directorate.

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-1999-0191

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
February 1999

3. REPORT TYPE AND DATES COVERED
Final Report, 6 Nov 96 to 5 Nov 98

4. TITLE AND SUBTITLE
The Cyberlink™ Interface: Development of a Hands-Free Continuous/Discrete Multi-Channel Computer Input Device (U)

5. FUNDING NUMBERS
C F41624-95-C-6002
PE 65502F
PR 3005
TA CH
WU 52

6. AUTHOR(S)
Christian Berg*
Andrew Junker*
Aric Rothman*
Ralph Leininger*
Grant R. McMillan**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*Brain Actuated Technologies, Inc.
139 East Davis St.
Yellow Springs OH 45387

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Human Effectiveness Directorate
Crew System Interface Division
Air Force Materiel Command
Wright-Patterson AFB, OH 45433

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-1999-0191

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***
The Cyberlink is an alternative controller that employs electromyographic, electrooculographic and electroencephalographic signals measured at the operator's forehead. The Phase I SBIR developed a pre-production prototype and demonstrated that operators are able to use it for continuous (point) and discrete (click) computer control with promising efficiency and accuracy. The Phase II effort transitioned this technology to a mature system that is available commercially. A dry electrode/headband system was developed for signal acquisition. A low noise bioamplifier and micro-controller performs signal conditioning and initial processing. Windows 3.1 and 95 drivers were developed to permit the Cyberlink to interface with third-party software. A suite of calibration, training and adjustment utilities also operate under Windows. The final evaluation compared the Cyberlink and a standard mouse in a two-axis target acquisition task that employed a Fitts' Law paradigm. Both mouse and Cyberlink performance could be modeled with Fitts' Law, although the mouse was about four times faster. This is an encouraging result, given the subjects much greater experience with a mouse. The Cyberlink is currently being employed as an assistive and therapeutic technology. Its rapid discrete input capability is being explored for several Air Force applications that would benefit from hands-free control.

14. SUBJECT TERMS
Biofeedback, Electromyography, Electroencephalography, Electrooculography, Control Systems

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

THIS PAGE INTENTIONALLY LEFT BLANK

Abstract

The Cyberlink prototype was developed in 1991 as an alternative controller using forehead biopotentials, acquired and processed in a novel way, as multiple computer input signals. A 1995 SBIR Phase I feasibility study showed that operators were able to use the interface for both continuous and intermittent computer control with surprising efficiency and accuracy. Operators performed successfully within minutes and accuracy improved with training. The measurement site was easy to access and reliable signals were routinely obtained. In other studies operators were able to demonstrate simultaneous independent control of at least two control signals derived from the single forehead site. Discrete control with under 0.2 second response times were measured.

The Phase II effort was undertaken to transition the technology to a mature preproduction prototype. Physiological analyses based upon literature review and experiments were performed to refine and expand the cursor control functionality . A dry electrode/headband system was developed. A low noise bioamplifier/microcontroller signal acquisition system was developed. A software suite of training, formatting and adjustment utilities was created, fully exploiting WINDOWS software tools to improve the graphical user interface (GUI). An automatic interface calibration scheme, sensitive to individual operator characteristics, was implemented. WINDOWS 3.1 and WINDOWS 95 mouse drivers were developed for Cyberlink interface control of third-party software applications.

Through an extensive program of research-based design, testing, analysis, redesign, and re-testing, the two-axis cursor control paradigm of the Cyberlink WINDOWS 95 mouse was made more accurate, stable and robust. At the same time, GUI improvements allowed quicker learning and ease of use of the system.

In a two-axis target acquisition task involving cursor positioning and clicking over randomly appearing targets, subjects' Cyberlink target acquisition times were consistent with Fitts Law and on average about four times longer than those observed with manual mouse devices. This is an encouraging result, particularly when considering the subjects' limited training with the Cyberlink interface and far greater experience with the manual mouse.

The results of the SBIR Phase II effort indicate that the Cyberlink interface is a viable mouse replacement computer input device with far-ranging applications. It can be used in the military to unload the pilot's hands during cockpit management tasks, to enhance robotics controllers, to augment human/computer interfaces, to enhance voice actuated hands-free controllers for such things as mobile computing, and as an assistance and therapeutic training device for veterans with disabilities. In the commercial sector the interface can be used as a hands-free mouse replacement, for relaxation/recreation or education as an alternative video game or synthesized music and art controller, and for the hands-free operation of disabled or special needs assistance devices, including internet access, environmental controls, wheelchair control and muscle stimulation control.

Important Note to the Reader

This report is intended for general distribution. The device described in this report is under continuing development for commercial applications by Brain Actuated Technologies, Inc. To avoid unintentional disclosure to parties unknown, those software and hardware components which are currently proprietary and trade secret are not discussed in detail. Additional information concerning proprietary or trade secret aspects may be requested from the authors.

CONTENTS

1.0 INTRODUCTION

1.1 Background

Contemporary Air Force systems have reached an unprecedented level of sophistication and complexity. Operators, routinely called upon to manipulate simultaneously a multitude of buttons, keys, switches and joysticks, are experiencing what has been termed "manual control overload". Alternative, non-manual computer input devices are currently being developed to lessen cockpit management demands and provide an additional, efficient and intuitive operator-machine interface.

Brain Actuated Technologies, Inc. (B.A.T.) in Yellow Springs, Ohio developed the first Cyberlink™ interface prototype in 1991 as an alternative, brain-body actuated, hands-free multi-channel continuous control interface.

By using biopotentials present on the surface of the head as control signals, the Cyberlink interface moves the site of control closer to the brain. The surface biopotentials, defined as a "BrainBody signal", are the summation of electrical activity from the brain in the form of electroencephalalographic (EEG) potentials and from the body in the form of electromyographic (EMG) and electro-oculargraphic (EOG) potentials.

In the initial hardware design, three hydro-gel surface electrodes were affixed to the operator's forehead by means of a cloth headband. The center electrode served as a reference/ground. The forehead was selected as the signal source due to the relative ease and minimal preparation involved in obtaining the signal. The relatively high level of EMG and EOG in the forehead signal were applied as additional physiological inputs, facilitating rapid training and rudimentary control of the interface.

The headband signal was conveyed along a coaxial cable to a hand-wired prototype bioamplifier/analog-to-digital converter. The digital signal was transmitted through the parallel (printer) port to the IBM-compatible PC's CPU where all signal analysis and display programs were resident.

The core program employed a new decoding algorithm (U.S. patent 5,474,082) developed by B.A.T. to allow a more rapid translation of the composite BrainBody signal into component frequency bands than was previously possible with the Fast Fourier Transform (FFT). In the initial design, two of these derived component frequencies, one a high theta rhythm at 6.25 Hz and the other a low beta at 13.25 Hz, became the analog continuous control signals for the vertical and horizontal movement, respectively, of a two-axis cursor in a computer maze game prototype.

1.2 First Studies

In Cyberlink pilot studies conducted in 1992, naive operators were first given a biofeedback display of the BrainBody frequency bands used for control resembling a 'graphic equalizer' spectral analysis. The height of the moving columns in a bar graph depicted, in real-time, the changing derived amplitudes of specific frequency bands. These 'brain-actuated' columns came to be known as "Brainfingers." The Brainfingers™ were color-coded to suggest specific cognitive states found, in the biofeedback literature and preliminary subjective Cyberlink studies, to be associated with the different primary EEG bands.

Brainfinger Color	Rhythm/EEG	Associated Cognitive State
blue	low frequency/theta waves	inattentive, first stages of sleep
green	medium frequency/alpha waves	unfocused attention, meditative, synthetic
red	high frequency/beta waves	focused attention, concentrating, analytical

The pilot subjects were next trained in a one-axis target acquisition task. The horizontal movement of a computer-generated pong paddle was proportionally mapped to the amplitude of a 13.25 Hz Brainfinger. The subjects learned to position the paddle to acquire moving targets (represented as pong balls) by increasing their Brainfinger amplitude to drive the paddle to the right and decreasing it to bring it back to the left. The Brainfinger frequency of 13.25 Hz was chosen to correspond to the frequency of control used in the Roll Axis Tracking Simulator evoked response experiments conducted at the Armstrong Laboratory, Wright-Patterson AFB, Ohio (McMillan, Calhoun, et al., 1994).

After approximately ten minutes experience with the one-axis pong task, the subjects were transitioned to a two-axis maze consisting of 50 walls. The horizontal motion of the game cursor was controlled by the 13.25 Hz Brainfinger while a 6.25 Hz Brainfinger simultaneously controlled the vertical motion. After a couple of attempts, most subjects succeeded in navigating through the maze in under two minutes but found it difficult to describe the specific mental and physical methods they were using to accomplish this.

A series of studies were designed to focus on single-axis control tasks to illuminate the 'inner workings' of Cyberlink control. The most important of these were performed in partnership with the US Air Force and are reviewed in detail in the following sections.

1.3 Target Acquisition Study

Under Logicon contract #F41624-94-600, a study was run for the Armstrong Laboratory at Wright-Patterson AFB, Dayton, Ohio, to evaluate the effects of training and individual differences on performance in a one-axis continuous control task with the Cyberlink interface (Junker, Berg, Terenzio, et. al., 1995). Methods for evaluating the relative contributions of EEG and EMG (as found in the forehead biopotentials) to control the Cyberlink interface at 13.25 Hz were developed. Results from this study provided insights into the effects of extensive training on performance with the Cyberlink Interface. Times to reach asymptotic levels of trained performance were obtained. Subject control strategies were identified.

Ten test subjects, seven male and three female, performed the Cyberlink target acquisition 'pong' task for a training period of 20 sessions at 150 trials per session. As before, the 13.25 Hz Brainfinger was proportionately mapped to the horizontal motion of the paddle. To help characterize subject control methods and strategies, EEG and EMG data was collected via the Cyberlink interface during task performance. Two piezoelectric vibration transducers mounted in the headband just above the subjects' right and left temples provided additional channels of signal data reflecting facial and eye muscle activity.

Four subjects had trial blocks in which they acquired 15 out of 15 targets and seven performed the task above an 80% accuracy level by their sixth session. The majority exhibited a significant degree of task learning over the course of the 20 sessions. Regression analysis on the difference between the subjects' task accuracy in the first and last quarter of their training and the results of pre-training questionnaires designed to quantify the subject's attitudes/anxiety towards computers and their fear of success indicated significant associations between these psychological factors and task learning.

Subjects were given both the ability to adjust the gain and response speed of the Cyberlink Interface, and the range sensitivity and centering of Brainfinger magnitude to control paddle position. They were instructed to find their own interface adjustment scheme for performing the target acquisition task. A comparison of the subjects' one axis cursor control methods, task accuracy scores, and user adjustment settings suggested that control style (EEG-based versus EMG-based) was more associated with certain adjustment combinations than with any particular level of task performance.

For targets to the right of center of the paddle range of movement, successful acquisition required relatively large control inputs on the part of the subjects. When the Cyberlink interface was set up with the nominal adjustment values many subjects had to resort to increased body activity to generate these large control inputs. This hypothesis was supported by an observed increase in the derived EMG signal and the vibration transducer signal.

With high gain, on the other hand, a smaller control input was required to move the paddle right of center. This was especially observed in one subject who chose to adjust the interface for high gain and slow response speed. In a post-experiment debriefing questionnaire this subject

reported that he was using primarily mental techniques to move the paddle, a contention corroborated by his extremely low EMG and piezo-vibration transducer signal levels.

Subjects selecting the nominal settings, on the other hand, reported using various combinations of physical methods (eye and facial muscle movements) and non-physical methods (visualizations, conceptual-cognitive tasks, emotional state changes, etc.) to control the paddle. These results led to a crucial redesign of the user interface adjustments facilitating and encouraging user exploration of the full range of control possibilities.

1.4 SBIR Phase I Studies

With the above results as a foundation, a Phase 1 SBIR effort was undertaken to determine appropriate directions for further development and possible commercialization of the Cyberlink interface (Junker, Berg, Schneider, & McMillan, 1995).

A study was conducted to evaluate in greater detail the relative contributions of various muscle (EMG-based) and non-muscle (EEG-based) control techniques and user-adjustment settings to Cyberlink task performance. Six subjects, four male and two female, performed 300 trials over 10 sessions in a station keeping task and a modified pong target acquisition task.

The response and control utility of four different Brainfinger frequencies was also investigated. Four representative Brainfingers were chosen to span the accepted EEG frequency bands: 6.25 Hz in the theta band, 9.50 Hz in the alpha, 13.25 Hz in the low beta, and 20.25 Hz in the mid-beta.

The pong target acquisition task was redesigned with a wider range of possible user adjustment values and a simplified, more intuitive graphical user interface. To gain insights into the user's ability to produce a constant output in Cyberlink cursor positioning, a station keeping task was created. Brainfinger magnitude proportionately controlled the horizontal movement of a small box in the display. Targets appeared in the various locations on the cursor's axis of movement and the subject moved the box over the target, attempting to hold a fixed position until the next target appeared.

A possible approach to training subjects to develop a more subtle, efficient, and internalized control methodology was investigated. An additional display of EMG signal activity was added to each of the two task displays. Subjects were instructed to keep the EMG signal activity display (an indicator of facial muscle activity) at a minimal level while performing the control task. Heavy EMG signal activity tended to cause the cursor to become extremely unstable or to exit the playing field, resulting in lowered task performance. In this way, high muscle-based control methods were negatively reinforced. This investigation provided an opportunity to discover what effect knowledge of EMG activity had on the ability to exercise more subtle control with the system.

Subjects were instructed to explore a large adjustment setting space and emphasis was placed on achieving what is defined as "a subtle control strategy". Settings chosen by the trained subjects provided information as to what desirable default adjustment settings might be. It was possible to correlate adjustment settings with performance success. The experiments provided an opportunity to observe interface setting differences between the two tasks and the four Brainfinger frequencies.

After five hours of training, one subject performed both tasks at a 92% accuracy level. Another subject performed at an 80% average success rate with little or no detectable facial muscle or eye activity involved in their control methodology.

For both tasks, performance, control strategies and techniques, and interface adjustment settings were found to vary according to the frequency band (Brainfinger) used for control. Analysis of the relationship between the subject's control technique, interface adjustment, and task performance indicated that subtle, internalized Cyberlink control is more associated with specific adjustment values than with any particular level of task success.

Correlation matrices between pong paddle and ball position, EMG signal, and multiple Brainfinger time histories recorded during performance of the target acquisition task showed that a majority of subjects had episodes where they appeared to exercise <u>selective</u> manipulation of the single Brainfinger used in the task. When subjects employed heavy eyebrow lifting and other gross facial muscle techniques to acquire targets, a broad-band response was observed in the signal data, but the precise mechanism(s), mental or physical, involved in generating selective narrow-band responses was unknown.

Signal data was collected in a control experiment in which the chief investigator performed a series of facial muscle actions most prominent among the subjects' observed physical techniques employed in Cyberlink target acquisition and station keeping. These data, although insufficient to expose the source of the subjects' occasional episodes of narrow-band control frequency manipulation, revealed relationships between signal patterns and specific facial muscle contractions. These relationships suggested the possibility of applying one or more of the facial gestures to create an EMG 'click' event (functionally analogous to computer mouse button clicks) for discrete commands.

A preliminary rule-based auto-adjustment program was designed and evaluated. A Cyberlink game involving ten Brainfingers manipulated sequentially to acquire a target moving slowly along the x-axis, called "SlowBall", was modified to provide baseline performance and signal data to an auto-adjustment algorithm for determining user-appropriate system gain and cursor offset values. When applied to the subject's performances of the target acquisition and station keeping tasks, these auto-adjusted user-interface values seemed to foster more subtle and efficient cursor control techniques without lowering task accuracy.

The opportunity to explore different controller designs was undertaken in the SBIR Phase I effort. Operators in Cyberlink control tasks, particularly the station keeping task, required some degree of output signal averaging to reduce the negative effect of cursor instability or "jitter" in

the resulting control action. An enigmatic noise component of the BrainBody signal was identified as the major contributor to jitter. However, the signal averaging, or "smoothing" required to raise effective signal-to-noise ratio to an acceptable level had the side effect of adding an unacceptable delay in the responsiveness of a system.

Various extended time base signal averaging methods and washout and lead compensation filters to reduce the effects of noise and delays on system performance were implemented. None of these refinements appeared to improve operator performance. Fortunately, in the process of developing them, it was discovered that a significant portion of the system instability and jitter was a consequence of unnecessarily high Cyberlink interface hardware ambient noise, a situation that could be corrected at its source. A new signal detection/amplification system with a lower noise floor and increased signal sensitivity was projected for development under the SBIR II effort reported here.

1.5 SIRE Studies

In the fall of 1995, a joint study was conducted in the Synthesized Immersion Research Environment (SIRE) at the USAF Armstrong Laboratory, Wright-Patterson AFB, Dayton, Ohio. Teams from Logicon Technical Services, Inc., Armstrong Laboratory, and B.A.T., Inc. collaborated to assess the Cyberlink interface as an alternative controller for virtual environments and tactical airborne applications (Nelson et al., 1996a and Nelson et al., 1996b). Cyberlink performance and skills acquisition were evaluated in a discrete reaction time task and a one-axis continuous tracking task in an immersive virtual reality flight simulator.

In work leading up to the SIRE studies an EMG pulsatile capability was demonstrated as a viable input signal for discrete commands. Most subjects quickly learned to create a timely EMG double pulse. In the prototype, a double pulse was chosen as the criteria for the EMG-click event to reduce the likelihood of unintentional 'clicking.'

In subsequent pilot tests two important discoveries were made:

1) when subjects were presented with a real-time history trace of their EMG signal with the click-event threshold represented as a dotted horizontal line above the trace and a computer-generated example of the requisite click waveform (appearing as a spike in the EMG trace) they could learn almost immediately to execute EMG-clicks more rapidly and just as reliably with a single EMG pulse, and

2) a variety of facial muscle actions could be applied to produce the requisite click waveform in the EMG, ranging from a short, concise eyebrow lift to a deliberate, hard blink.

This single pulse EMG-click was adapted to provide the control input in the SIRE discrete control study. Five naive subjects, three males and two females, performed 10 experimental sessions at 50 trials per session of a simple reaction task; generating Cyberlink EMG-clicks as quickly as possible in response to a critical visual stimulus appearing among a suite of avionics

displays on a computer monitor. The subjects were given general instructions in 'EMG-clicking' and were encouraged to explore various click techniques to find their own preferred method, but received no training in any specific technique.

The results confirmed that discrete Cyberlink control is intuitive and can be mastered quickly. With no special coaching, subjects' mean reaction times improved dramatically over their initial experimental sessions, reaching asymptotic performance before the fifth experimental session. Response accuracy was found to be extremely high, approximately 98%, and reaction times fell between 180-200 msec, a range considered to be the limit of simple reaction time to visual stimuli (Keele, 1986). Several subjects actually achieved 15-20% faster reaction times with the Cyberlink EMG-click than with a manual button. The width or duration of the subjects' EMG-click responses decreased approximately 47 msec over the experimental sessions, indicating an improvement with training in the precision and efficiency of their EMG-click technique.

Of particular interest in this study were the results of a self-report inventory, the Yoshitake Symptoms of Fatigue Scale (Yoshitake, 1978), indicating that the Cyberlink interface can be used for tasks requiring the production of a high density of discrete commands and responses without fatiguing the user.

In the continuous tracking experiment subjects used the 13.25 Hz Brainfinger to navigate through a series of hoops defining a flight path projected on a 40-foot virtual reality dome. This was a continuous control task on the x-axis functionally similar to the pong task, but with the added visual feedback and realism of a large scale, fully immersive, first-person-perspective graphic display and simulated roll motion in the direction of travel (right or left). To achieve more stability, a null-zone was added to the basic lateral control paradigm whereby Brainfinger magnitudes exceeding an upper power threshold initiated rightward movement, those falling below a lower power threshold initiated leftward motion, and those hovering in the space between the two thresholds initiated no lateral movement.

12 naive subjects, ten males and two females, receiving only generalized instructions in Cyberlink continuous control and no coaching in specific techniques, performed 100 trials over ten sessions, completing a NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) at the end of each session.

Tracking performance, as measured by RMS error and percent time on target, improved dramatically across the sessions. In some cases, asymptotic performance still hadn't been achieved by the subject at the end of the study although percent of hoops traversed had exceeded 90%. In all cases, self-reported workload ratings decreased significantly across the sessions.

The results of a Cyberlink skill retention follow-up study were also promising. In all measures of task accuracy and efficiency, the subjects resumed at their prior level of performance after a six month hiatus, suggesting a high retention rate for acquired Cyberlink control skills. Similar good retention of manual tracking skills has been reported in a variety of studies (Poulton, 1974).

1.6 Prelude to SBIR Phase II

SBIR Phase I follow-up studies with other Cyberlink tasks, conducted in late 1995, continued to demonstrate the general utility of the four Brainfingers already applied to continuous control and revealed several more Brainfinger candidates. Phase I SBIR results had suggested that certain control techniques were Brainfinger-specific. Follow-up studies revealed that Brainfingers at the low frequency end of the BrainBody spectrum (1.1 - 6.25 Hz) seemed to be particularly responsive to ocular movements whereas the high frequency Brainfingers (20.25 - 25.5 Hz) appeared to respond more to subtle scalp and eyebrow movements, as well as what could be called a purposeful, yet non-muscular, focus of attention.

By the end of 1995, nearly a hundred operators had used the Cyberlink system in a variety of control tasks and studies. This research established that the forehead signals used for continuous and discrete control were consistent and intelligible and that they could be affected by most users with some degree of intention and frequency-selectivity after minimal training. In addition, Cyberlink control did not produce apparent undue fatigue or negative side effects, even after prolonged use.

The success at different frequencies, the observation that different control techniques are effective at different frequencies, and enhancements in the EMG-click algorithm arising from the SIRE study, suggested the possibility of a 2-axis continuous plus discrete alternative controller application of the BrainBody actuated technology.

As a result, the primary objectives of this SBIR Phase II effort were formulated: to develop the controller interface described above and to transition it from a proof-of-concept prototype to a practical, fully functional, hands-free, pre-production prototype input device.

Achieving these objectives depended on further development of the BrainBody actuated technology foundations. To expand the functionality and improve the accuracy of the controller and to develop suitable applications to operational settings, a more detailed understanding of the forehead control signals and their muscle, brain, and ocular sources was required.

2.0 TOWARDS A BETTER MODEL

2.1 SBIR Phase II Literature Review

A comprehensive library and internet search of the pertinent EEG, EMG, and EOG biofeedback and source localization literature was undertaken in four phases from autumn 1995 to winter 1996 to gain an in-depth understanding of the nature and physiological origins of the forehead biopotentials. The topics researched included:

1) Multi-channel EEG brain topographical mapping and other source localization studies carried out in the process of isolating EEG origins of surface electrode signals (Marks & Issac, 1995; Poline & Mazoyer, 1994; Wilson, 1994; Lancaster, Fox, et al., 1994; Inouye et al.; 1993, Baumgartner, 1993; Luders et al., 1992; Montgomery et al., 1992; Gevins & Illes, 1991; Wong, 1991; Weiss et al., 1987; Hjorth, 1986; Fox et al., 1985; Uemura et al., 1983; Gevins et al., 1980 and Lindsley, 1952),

2) Comparison studies of source localization from the magnetoencephalogram (MEG) in simultaneous EEG studies (Baumgartner, 1993; Wikso et al., 1992; Kaufman, 1993 and Deecke et al.,1982),

3) Cognitive state and physiological correlates of specific EEG rhythms and brain potentials (Linden et al., 1996; Steriade, 1996; Munk et al., 1996; Ganis et al., 1996; Miller, 1996; Gevins et al., 1995; Pfurtscheller & Pregenzer, 1995, Porjesz & Begleiter, 1995; Williams, Rippon et al., 1995; Williams, Zaveri, et al. 1995, Birbaumer et al., 1994; Freeman & Barrie, 1994; Jobert, 1994; Jokeit & Makeig, 1994; Pope et al., 1994; Sterman et al., 1994; Sterman et al., 1993; Inouye et al., 1993; Freeman, 1993; Freeman & Barrie, 1993; Dujardin et al., 1993; Besson & Kutas, 1993; Sobotka et al., 1992; De Toffol et al., 1992; Paller & Kutas, 1992; Sterman et al., 1992; Bullock, 1992; Gevins et al., 1991; Klorman, 1991; Linden et al., 1991; Sumathy & Krishnan, 1991; Mast & Victor, 1991; Henriques et al., 1990; Kutas & Van Petten, 1990; Lubar, 1989; Pfurtscheller & Berghold, 1989; Kutas & Hillyard, 1988; Schwartz, 1987; Speil, G., 1987; Banquet, 1984; Kasamatsu & Hiri, 1984; Gratton, Coles, & Donchin, 1984; Elbert et al., 1984; Gevins & Schaffer, 1980; Kutas & Hillyard, 1980; Bird et al., 1978; Cazard, 1976 and Lindsley, 1952),

4) Biofeedback literature providing additional data on the frequency ranges of various bioelectric signals (Williams, Rippon et al., 1995; Blanco et al., 1995; Othmer et al., 1991 and Grossman & Weiner, 1966),

5) Techniques for isolating EMG, EEG, and EOG signals and automated recognition of artifact and system noise in EEG, EOG, and EMG (Blanco et al., 1995; Verleger, 1993; Zheng et al., 1993; Takano et al., 1993; Roessgen et al., 1993; Gasser et al. 1986; Berg, 1986; Barlow, 1983; De Oliveira, 1983; Gratton, Coles, & Donchin, 1983; Bird et al., 1978; Gevins et al., 1977 and Carpenter, 1948),

6) EEG slow potentials (SP) and response-oriented cognition: contingency evaluation, attention, expectancy, and response preparation (Cooper et al., 1989; Achermann & Borbely, 1987; Deecke et al., 1982; Deecke & Grozinger, 1976; and Gotman et al., 1973),

7) Neural net-aided recognition of sensory and cognitive processing in the EEG and automated on-line EEG pattern recognition (Anderson et al., 1995a-c; Pfurtscheller & Pregenzer, 1995; Flotzinger, Pfurtscheller, et al., 1993; Peltoranta & Pfurtscheller, 1994; Dorffner, 1995; Gevins et al., 1995; Veselis, 1993; Jando et al., 1992; Bartlett, Makeig, et al., 1995; Gabor, 1992; Gevins & Leong, 1992; Gevins & Illes, 1991; and Nakamura et al., 1992),

8) EEG and EOG monitoring of vigilance, alertness and sustained attention and neural human-system interface technology (Makeig & Jung, 1995; Jung & Makeig, 1995a-b; Jung & Makeig, 1994; Makeig & Inlow, 1992; Gevins et al., 1991; Makeig et al., 1990; Moore-Ede et al., 1989; and Matousek & Petersen, 1983),

9) EMG/EOG biofeedback and frontalis muscle tension/relaxation (Heetderks & Schwartz, 1995; Harwin et al., 1995; and Grossman & Weiner, 1966),

10) EMG-based discrete control and reaction time (Nakajima, 1995; Ulrich & Miller, 1994; Bartz, 1979 & Laszio et al., 1977),

11) Visual imagery, motor processes and EEG activity (Williams, Rippon et al., 1995; Marks & Issac, 1995; Issac & Marks, 1994; Weiss et al., 1987; Farah, 1988 & '84 and Farah et al., 1985; Marks et al., 1985, Davidson & Schwartz, 1977; and Short, 1953),

12) Perceptual-cognition, visual imagery, visuo-spatial tasks, intense vigilance, voluntary planned (willful) decisions correlating with enhanced beta 2 and gamma band activity and suppressed alpha in the prefrontal cortex (Hotz, 1996; Chorlian et al., 1995; Searight et al.,1995; Passingham, 1995; Goldman, 1995; Williams, Rippon et al., 1995; Ford et al., 1994; Birbaumer et al., 1994; Freeman, 1993; Freeman & Barrie, 1993; Oscar-Berman & Hutner, 1993; Jagust et al., 1992; Paller & Kutas, 1992; Shimamura et al., 1988; Haxby et al., 1986 and Shepard & Podgorny, 1978),

13) The use of Raven Progressive Matrices (selection of an abstract shape from a set of four alternatives) as a cognitive perceptual task and visuo-spatial stimulus to evoke beta 2 and gamma band EEG responses in the prefrontal cortex (Rippon, 1990 and Scheblanova, 1984).

14) EEG-based control interfaces (McMillan, 1995, McMillan et al., 1995; Wolpaw et al., 1991; Junker et al. 1988 and Junker et al., 1987), and

15) Existing, contact dry electrode technology (Taheri, 1995; Prutchi et al., 1993; Bourland et al., 1978; Betts & Brown, 1976; David & Portnoy, 1972; Bergey et al., 1971; Potter & Menke, 1970, and Johnson & Allred, 1968).

2.2 Literature Search Results and Theoretical Model Formulation

Although much of the literature disagreed on certain topics (e.g., the precise frequency ranges of the primary bands of the EEG spectrum, the degree to which various source localization methods can be said to truly isolate desired electrocortical signals, etc.), there was a meaningful consensus on several major points crucial to this SBIR II effort:

1a) In the EEG, activity in the delta through theta bands (approximately .5 Hz to 7.5 Hz) tends to increase as focus of attention or level of arousal diminishes, i.e., during extreme drowsiness, the early or "slow wave" stages of sleep, when there is structural damage to areas of the brain associated with the purposeful focus of attention, or when the subject has Attention Deficit/ Hyperactivity Disorder (AD/HD).

1b) Blinking and eye movements produce EOG transients in the delta and low theta bands which are difficult to distinguish and separate from low frequency EEG.

2) EEG slow potentials (possibly reflected in time-averaged magnitudes of very low frequency Brainfingers) are highly correlated with the velocity of target movement in a visual pursuit tracking task.

3a) Alpha rhythms (approximately 8 to 13 Hz) tend to become enhanced in the prefrontal cortex (and other brain locations) when subjects are aware but relaxed and when their attention is diffused or defocused, their eyes are defocused, or when they are immersed in a meditative or hypnogogic state.

3b) Alpha rhythms are suppressed in the prefrontal cortex (and other locations) during the mental rotation of imaginary objects, concentration on mental arithmetic, tasks with high cognitive demands, situations of high and complex task load, the self-generation of imagery, complex information processing, and during periods of effortful or concentrating attention and intense vigilance or arousal.

4a) Beta 2 rhythms (approximately 20 to 30 Hz) and Gamma rhythms (greater than 30 Hz) are enhanced in the prefrontal cortex (and other locations) during activities or stimuli that tend to suppress alpha; the effortful focus of attention or intense vigilance, the planning of the order and timing of future behavior based on recent past experience, mental rotation and other visuo-spatial and cognitive perceptual tasks such as Raven Progressive Matrices, complex and periodic music stimuli, REM or "active information-processing" sleep, etc.

4b) Overall power and/or irregularity (entropy), in the beta 2 and gamma bands also increases during calculation processing, complex visual-memory problem solving, visual feature binding and segregation, adaptive behavior based on 'shifting rule sets', abstracting (i.e., ascertaining principles or rules governing a particular task) and visual imagery; abilities all found to be greatly impaired in people suffering from structural damage to the prefrontal cortex and the frontal system due to lesions, prolonged alcoholism or other causes.

4c) Power in the gamma and beta2 bands is attenuated during deep dreamless sleep and central anesthesia and when the subject has AD/HD or certain forms of Autism.

This information was evaluated to generate the following hypotheses specific to the various control signals obtainable (or believed to be obtainable) by the Cyberlink Interface:

1) **HYPOTHESIS THETA$_1$ - long-term, time-averaged magnitude increases of the low frequency Brainfingers will reflect certain internal subjective states known to enhance EEG power in the theta or delta bands, however…**realistically, operators can not be expected to learn to position the 2-axis cursor (or other features controlled by a low frequency Brainfinger) by shutting down their higher brain functions, becoming extremely drowsy, or entering slow-wave sleep.

2) **HYPOTHESIS THETA$_2$ - short- and mid-term time-averaged magnitudes of low frequency Brainfingers (corresponding to the theta and delta EEG bands) can be increased in an intentional and timely manner through ocular activity, such as lateral eye movements and high-density blinking, for reliable and selective control of one axis of the 2-axis cursor.**

3) **HYPOTHESIS DELTA- time-averaged magnitudes of very low frequency Brainfingers, which may reflect EEG slow potentials, may unintentionally correlate with displayed cursor velocity.** As subjects unconsciously visually track the cursor across the display they may, in effect, be evoking a low frequency Brainfinger response which in turn may create spurious cursor movement. Therefore, certain very low Brainfinger frequencies may need to be avoided for positioning the cursor.

4) **HYPOTHESIS ALPHA - mid- and long-term, time-averaged magnitude increases of the mid-frequency Brainfingers (as detected on the forehead/pre-frontal site) will reflect certain intentional subjective state changes that enhance or suppress power in the EEG alpha bands.** Specifically, meditation/relaxation and the volitional defocusing of visual attention should prove to be practical methods for controlling features set to a mid-frequency Brainfinger in situations that are not time-sensitive (e.g. the modulation of musical events).

5) **HYPOTHESIS BETA/GAMMA$_1$ - the effortful focus of attention on a perceptual cognitive task presented on the display, concentration on visual imagery or mental rotation, or listening to complex and periodic music stimuli can be expected to evoke mid- and long-term time-averaged magnitude increases in the high frequency Brainfingers (as detected at the forehead/prefrontal site) corresponding to similar known responses in the Beta$_2$ and Gamma EEG bands.** Specifically, the above responses may prove to be practical methods for control of features set to a high-frequency Brainfinger in situations that are not time-sensitive.

6) HYPOTHESIS BETA/GAMMA$_2$ - the effortful focus of attention on a perceptual cognitive task presented on the display, concentration on visual imagery or mental rotation, or listening to complex and periodic music stimuli can be expected to evoke an increase in the entropy or irregularity of the high frequency Brainfingers (as detected on the forehead/prefrontal site) corresponding to similar known responses in the Beta$_2$ and Gamma EEG bands. This irregularity might be characterized as a 'spread' in the variability of the sampled Brainfinger magnitude values over a sliding sample window and used to create selective, efficient, non-muscular control of features in situations that are not time-sensitive.

7) HYPOTHESIS BETA/EMG - subtle contractions of the frontalis, masseter, temporalis, and other facial muscles within a certain proximity about the sensor locus, will cause immediate transients and short-term time-averaged magnitude increases, most pronounced in the high frequency Brainfingers (above 18 Hz), affording rapid, reliable and selective control of one axis of the two-axis cursor.

2.3 Testing and Refining the Model

The seven critical hypotheses were tested through a series of pilot studies designed to create an ever-expanding database on the origin and optimization of BrainBody control signals and to evolve and refine the theoretical model.

1) Test of Hypothesis Theta$_1$: Sleep Study - an interesting study confirming Hypothesis THETA$_1$ was conducted with a severe brain trauma patient at a Mental Retardation/Developmental Disability center in Akron, Ohio. This man, a completely "locked-in" quadriplegic, exhibited a tendency to become agitated or distressed when aroused, but to fall asleep rapidly and automatically upon relaxation. He was connected to the Cyberlink and a special brain-actuated music program was engaged which rewarded low beta$_2$ activity (interpreted as low relative time-averaged magnitudes of the high frequency Brainfingers) and high theta activity (low frequency Brainfingers) with relaxing and soothing music.

His experience with the Cyberlink became a cycle of immediate relaxation followed by very high observed power in the theta band (displayed as low frequency brain fingers) and sleep, followed by sudden arousal (his caretaker would then wake him up), followed by relaxation as he again responded to the music program, followed by high theta and sleep, and so on. This low frequency Brainfinger control technique was judged to be too impractical for most operational settings.

2) Test of Hypothesis Theta$_2$: Eye Motion Studies - in one experiment, the chief investigator modified a Cyberlink headband harness to allow placement of the sensors on alternate sites around the eye. Signals collected during basic ocular motion (upward/downward glancing, left/right glancing, blinking, etc.) were compared for each of the alternate sites. In another experiment, ten subjects performed a more varied series of eye motions with the sensors on their forehead in the standard headband. The results of both experiments suggested that lateral eye movements produced more reliable and prominent transients in the low frequency Brainfingers

(measured at the forehead site) than either vertical eye movements or blinking. As a result, the design of the cursor control model was modified (see following section).

3) Tests of Hypothesis Alpha:

a) Meditation/Relaxation Study - long-term BrainBody and EMG signal data was collected from subjects wearing the Cyberlink interface while meditating. The subjects included two professors of Eastern meditation techniques at local colleges and several of their students. Non-meditation experimental controls included reading text silently, closing eyes and listening to a recorded voice, and looking at pictures. Analysis of the signal data confirmed that significant long-term increases in the time-averaged magnitudes of the mid-frequency Brainfingers (particularly those corresponding to low alpha) accompany self-reported episodes of light or deep meditation.

b) Optical Defocusing Experiment - Before confirmation was found in the literature search, the chief investigator noted a connection between his alpha Brainfinger response and the intentional defocusing of his eyes. Whenever he defocused his eyes he observed a sudden increase in the displayed height (magnitude) of his mid-frequency Brainfingers. To determine how general this effect might be, ten subjects looked at stereograms (composite '3D' images that require self-adjustment of visual focal length to see the imbedded image) while their BrainBody signal data was collected with the Cyberlink. The results in this visual defocusing experiment were ambiguous because only two subjects reported they could see the embedded stereogram images. In subsequent studies, approximately 30% of the sample population observed they were able to produce the 'alpha boost' response by defocusing their eyes.

4) Test of Hypotheses Beta/Gamma$_{1\text{-}2}$ - Ten subjects performed three cognitive perceptual tasks (Raven Progressive Matrices), silently read two lines of written text, and relaxed with their eyes closed and open (to provide baselines) while their BrainBody signals were being recorded with the Cyberlink interface and a special data collection program.

As the subjects performed the tasks, a video camera monitored their faces and their signal data was written to a text file for subsequent analysis in MS Excel and visual inspection in a multi-channel signal playback program. The video camera output was synchronized and superimposed with the signal playback display using a 'genlock' device providing evidence of any concurrent facial muscle activity to aid in evaluating the purity of the collected prefrontal EEG signals.

The results showed that nine subjects produced a significant increase above their baselines in the variability of the 35 Hz and 40 Hz Brainfinger magnitude values over a sliding sample window (of a particular duration) concurrent with the presentation of the Raven Matrices.

As a result of these and other tests designed to clarify points that had remained ambiguous after the literature review, the Cyberlink control theoretical model had become more rigorous, facilitating and informing improvements in the design of what came to be known as the two-axis 'control paradigm.'

2.4 Evolving The Control Paradigm

In considering the original (pre-SBIR II) two-axis control model in light of the new data, and as newly developed low-noise hardware permitted higher controller gain, the fundamental design elements of the control paradigm (CP) were identified and expanded.

<u>Elements of Two-Axis Control Paradigm Design</u>

CP Element	*Definition*	*Possibilities - *Tested as of mid-SBIR II*
#1: Signal to Axis Mapping (for Continuous Control)	Which forehead signal controls: X (lateral cursor movement) ? Y (vertical cursor movement) ?	a) *X = 13.25 Hz low beta Brainfinger & *Y = 6.25 Hz high theta Brainfinger b) X = any Brainfinger at 1 - 40 Hz, or EMG, or EOG & Y = any of the above, not same as X
#2: Motive Signal Characteristic	Which attribute change in the signal of interest is used to generate cursor movement ?	a) *time-averaged magnitudes ($power_1$) b) *median/upper and lower quartile ($power_2$) c) 'spread' of magnitude samples (chaos) d) waveform analysis (shape)
#3: Cursor Motion Formula	In what direction, proportion, and velocity will the cursor move in response to a given attribute change in the signal of interest (motive signal Δ)?	a) **proportional* - cursor position is direct function of Brainfinger magnitude. b) **mono-velocity* - cursor moves at fixed speed when upper or lower magnitude thresholds exceeded. c) * various *proportional/velocity* hybrids d) * *velocity* - cursor velocity is a direct function of magnitude.
#4: Cursor Response Adjustment Method(s)	Presence and application of user-defined and/or auto-adjusted interface parameter settings: how far (gain), at what velocity (cursor speed), centered at which display position in the axis of motion (offset), will the cursor move in response to a given motive signal attribute change?	a) *user adjusted cursor offset, speed & gain & no continuous auto-adjust b) *user adjusted offset and cursor speed with continuous auto-adjusted gain c) * user-adjusted overrides of auto-calibrated initial offset and gain values
#5: Cursor Behavior During Defined Signal Stasis (zero Δ)	Function and proportions of a 'null zone' or non-control region within which the motive signal Δ is defined as a zero control input and the cursor motion to be produced during these episodes of zero input.	a) **original* - cursor stationary when motive signal within user-defined null zone. b) *linear* - linear pre-programmed motion when motive signal within null zone. c) *polar* - radial pre-programmed motion when motive signal within null zone.
#6: Mapping of Discrete Command(s) to Mouse Button and Other Program Inputs	Which signal transients making which pre-defined power threshold crossings will activate which Mouse button, keyboard, cursor motion/response attributes, or other program functions?	a) *EMG spikes activate left Mouse button clicks and/or program item selections. b) *EEG spikes at a user-defined Brainfinger frequency activate left Mouse button clicks and/or program item selections. c) *EOG spikes activate left Mouse button clicks and/or program item selections d) Additional transients and waveforms activating cursor and other functions

Initial Development of the Two-Axis Control Paradigm

With the expanded control model as a blueprint, the following design element revisions and enhancements were implemented:

Revised Element #1:

Lateral (X) Brainfinger Re-mapping - Prior to the SBIR Phase II effort, the prototype two-axis control model used a low beta Brainfinger at 13.25 Hz to control the cursor horizontal axis. Literature and in-house experiments had indicated that, due to the lateral arrangement of the Cyberlink headband sensors and the fact that the human eye is a bioelectro-chemical dipole, typical lateral ocular movements result in pronounced transients in the low frequency forehead biopotentials (1.0 - 6.5 Hz Brainfingers).

Consequently, lateral cursor control was re-mapped to a low frequency Brainfinger at 6.25 Hz to make it more intuitive, learnable and reliable. After this change, operators found lateral control simple to understand and execute: glance right and the cursor moves to the right; maintain stationary gaze and the cursor moves to the left.

Vertical (Y) Brainfinger Re-mapping - At first, the low beta 13.25 Hz Brainfinger was assigned to the remaining (Y) axis; but tests with dozens of naive and experienced Cyberlink subjects in the two-axis maze task suggested that the separation or independent response between the two motive signals (required for successful two-axis control) might be improved if they were spread further apart on the BrainBody spectrum. After further tests at various control frequencies suggested by the literature search (see Hypothesis Beta/EMG), the vertical axis was mapped to a higher frequency beta$_2$ Brainfinger at 25.5 Hz and the lateral axis was mapped to a delta Brainfinger at 1.25 Hz.

In subsequent tests and studies, this revised Brainfinger mapping significantly enhanced two-axis task performance accuracy and efficiency. With maximum frequency spread between the two Brainfingers used for control, the horizontal/vertical independence required for effective two-axis cursor control was greatly improved.

Revised Element #2 (and 4):

Median and Upper/Lower Quartile Magnitude Values for Motive Signal Characteristic and Basis for Auto-Adjust - after the pre-production prototype low-noise bioamplifier/interface (see section 3.5) hardware became available, Dr. Henry Jex (an expert consultant in manual control) met with Brain Actuated Technologies personnel to evaluate the controller interface software and discuss possible improvements. The addition of lead generation or lag to the system to stabilize the human operator input was reconsidered. Due to the more stable cursor response dynamics and higher controller gain levels made practical by the improved signal to noise ratio of the new interface hardware, it was decided that the best approach would be to eschew additional dynamics to the system, such as lead compensation etc., but to refine the auto-adjustment of the interface.

Dr. Jex suggested that this would enhance the richness of the feedback so that the human operator can more easily provide his or her own lead generation.

Towards this goal, an alternative statistical signal analysis was proposed employing median and upper and lower quartile values as a more accurate characterization of Brainfinger magnitude for cursor positioning and auto-adjustment of controller gain and bias. Subsequent implementation and testing of this approach yielded undetectable improvements in cursor control and it was eventually abandoned pending further study.

Revised Element #3:

Velocity Cursor Motion Formula - tests with early training applications indicated that the *mono-velocity* (single speed) formula occasionally produced more predictable cursor response than the *proportional* formula in certain two-axis control contexts, but the analog, multi-speed response experienced with the *proportional* formula was lost. To recover this advantage, a velocity method of cursor positioning was developed. Cursor speed was varied in accordance with control Brainfinger magnitude. Comparison tests of this variable *velocity* with the earlier *mono-velocity* controller showed that accuracy of two-axis cursor positioning improved dramatically due to the increased degree of control feedback provided by the *velocity* controller.

Continuing tests of these 'first generation' control paradigm revisions yielded an unexpected result: while the Brainfinger signal to axis re-mapping improved performance in all two-axis control scenarios and for all cursor motion methods, the original *proportional* formula proved to be the most effective cursor motion method developed thus far in the one-axis pong task where cursor movement had to be synchronized with an incoming target.

Also, a velocity controller incorporating high cursor speed and a small null zone enabled subjects to complete the two dimensional maze task rapidly, but was found to be excessively unstable in other two-axis settings more closely resembling the WINDOWS desktop 'open' environment. Was the presence of guiding and motion-limiting walls in the maze a factor?

After these first findings, it became clear that continued evolution of the control paradigm would require the development of further training and testing applications to model the full range of possible cursor performance settings.

3.0 HARDWARE DEVELOPMENT UNDER SBIR PHASE II

3.1 The Dry Surface Electrodes

Regardless of the application, the Cyberlink Interface's ease of utilization is paramount. The primary interface between the human and the Cyberlink interface is the sensor array that is attached to the subject's forehead.

In the controlled laboratory setting of the SBIR I and SIRE studies, the electrode measurement system used hydro-gel surface electrodes for obtaining forehead biopotentials. The electrode harness was noninvasive, and relatively easy to connect to the subject. However, excessively dry forehead skin required hydration with water while excessive oil on the skin had to be removed with an alcohol swab in order to reduce surface electrical resistance and obtain acceptable performance.

Because the electrolyte on the electrodes was a hydro-gel colloid it tended to dry out when not in use. It was often necessary to hydrate each electrode before use. Even special packaging and storage methods were inadequate to prolong shelf life beyond a dozen or so uses.

Therefore, a practical dry electrode system needed to be developed for improved durability, ease of use, reliability, and performance in all operational settings. Candidate electrodes as reported in the literature were evaluated (Prutchi et al., 1993, Bourland et. al., 1978; Betts et al., 1976; Bergey et al., 1971; Potter & Menke, 1970; and Johnson et. al., 1968). Some of these required skin abrading and/or the application of electrolyte preparations.

Prototype stainless steel dry electrodes had been fabricated by B.A.T., Inc. just prior to the initiation of this SBIR Phase II, and added to a modified headband harness. Preliminary performance tests showed that, although they appeared to provide improved durability and shelf life, required minimal skin preparation and exhibited reduced D.C. offset (and thus reduced input amplifier saturation), impedance figures were between 70 K and 1,000 K ohms, significantly higher than those typically obtained with the hydro-gel electrodes.

High impedance electrodes promote the corruption of the forehead signal by noise and power line frequencies, particularly if the length of the electrode lead is excessive. It is possible to incorporate shielding in the lead to decrease noisy interference, however, the shield contributes to distributed capacitance and can lower the input impedance to the bioamplifier to the point where high frequency components of the signal are greatly attenuated.

This relatively high impedance may explain the subtle but detectable degradation in the accuracy and "feel" of cursor control reported by experienced subjects using the stainless steel electrodes in one and two-axis Cyberlink tasks.

Consequently, a silver chloride-plated, carbon-filled plastic sensor system was developed for this Phase II effort by B.A.T., Inc. working in conjunction with an outside contractor (Figure 1).

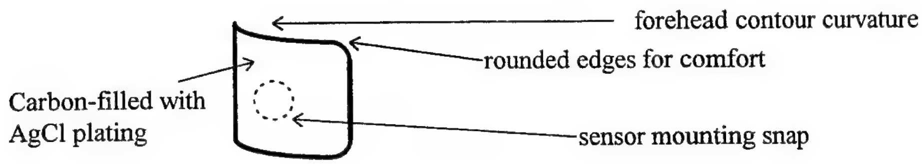

Figure 1. Dry Electrode Features

After an iterative process of testing, redesign, refabrication, and retesting extending over the length of the SBIR II contract, the silver chloride-plated sensors were perfected. The finalized pre-production version exhibits the following characteristics:

1) improved resistance to corrosion and oxidation,

2) a snap-on headband mounting system for easy removal for cleaning and maintenance,

3) minimal or no skin preparation required in most operational settings,

4) forehead contour curvature (horizontally) for improved fit,

5) high durability and longevity, in some cases maintaining operational levels of performance for several months of continuous use,

6) very low impedance (< 50 K ohms) and noise levels typically obtained with little or no skin preparation, and

7) performance equal to or better than the hydro-gel electrodes in direct comparison tests.

3.2 Sensor Preparation: Electrolyte Cream to Aloe Vera Gel Moisturizer

Before the development of the Cyberlink dry surface electrodes, the hydro-gel electrodes that were employed required hydration prior to each use. Similarly, the user's forehead was often prepped with tap water with a moist cloth or eyedropper. Impedance values obtained when these preparations were observed were as much as 95% lower than when the electrodes were applied with no preparation.

As the dry surface electrodes became operational under this SBIR II contract, preliminary performance studies showed that impedance levels obtained with no preparation were often as low as those obtained with the hydro-gel electrodes with preparation.

Impedance levels were found to be negatively impacted, however, when the forehead skin was excessively dry or oily. At such times a conductive cream electrolyte was found to bring impedance back down to optimal levels (< 50 K ohms). After several months of use in pilot tests, focus studies, and general Cyberlink development applications, many users began to report the conductive cream made their foreheads feel "greasy" and seemed to contribute to clogged skin pores and occasionally forehead skin blemishes.

As a result, a common EKG conductive gel was tested. This gel, although mitigating the earlier side-effects, contained a salt which caused a pitting in the silver chloride platting and significantly reduced the dry sensors' shelf life. Some users experienced a mild skin irritation.

The third and final solution was discovered when one B.A.T., Inc. researcher ran out of the electrolyte gel and tried aloe vera moisturizing gel as a substitute. Promising initial results led to more exhaustive comparative testing which indicated that consistent, very low impedance levels could be obtained with no "greasy" forehead effect or skin irritation. It was later discovered that aloe vera gel contains natural electrolytes which minimize corrosion of the silver chloride sensor platting.

3.3 The Sensor Harness

The Sensor Harness evolved gradually over a period of two years as B.A.T., Inc. and a subcontractor worked through dozens of less than perfect versions to the present fully operational design. This finalized version embodies (Figure 2):

1) special touch proof connectors to the interface unit,
2) a composite jack and harness using three potted plastic snaps for easy sensor removal,
3) durable joints and connections,
4) shielded high strength tensile wire in the sensor cable, and
5) very low signal corruption by high frequency noise.

3.4 The Cloth Headband

A special cloth headband was developed by B.A.T., Inc. and fabricated by an outside contractor (Figure 2). It was designed to be comfortable, durable, and to allow easy removal and reinsertion of the sensor harness for headband washing, and to allow the sensor cable to lead from either the left or right side.

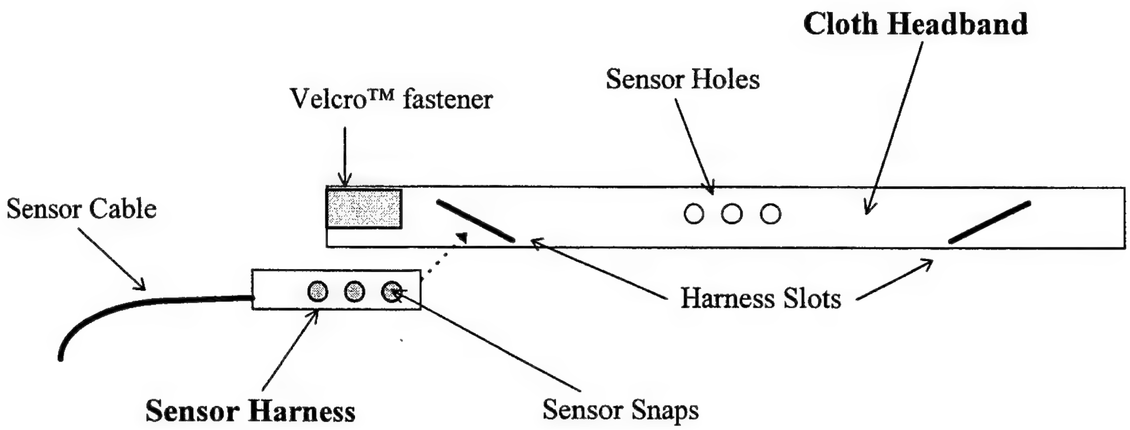

Figure 2. Headband and Sensor Harness

3.5 The Interface Unit

Pre-Phase II studies had established that a bioamplifier with extremely high sensitivity needed to be developed before the interface could realize its full performance potential. Sufficient sensitivity to amplify and faithfully represent very small signals resulting from both brain and subtle muscle activity was required. These signals are of highest interest because the Cyberlink interface's prime focus is to approach an ideal situation where control is essentially "thought actuated". These small signals can range from as low as 0.5 microvolts to strong frontal-lobe alpha waves of 15 to 50 microvolts. The obvious problem with acquiring a signal that is in the order of 0.5 microvolts is the noise floor of the amplifier circuitry. Both active and passive circuit elements contribute to the production of noise and reduce the signal-to-noise-ratio of the system.

Higher controller gain was expected to allow less control signal filtering in the software, more efficacious feedback to the user, and therefore better cursor control. Nevertheless, without a reduction in perceived system noise, operators could not successfully operate at higher controller gain.

To compound the problem, while the human operator is producing these very subtle signals, spontaneous muscle activity on the forehead often produces very large signals that can have voltage peaks in the millivolt range. Some of these signals are very low frequency and cause the integrated circuit amplifiers to saturate at the power supply limits for a period of time, thus causing the loss of information until the circuits recover. On the other hand, these very large

signals can also be of interest and be utilized by the Cyberlink interface as part of its control mechanism.

The bioamplifier had to incorporate an improved dynamic range, e.g., high sensitivity to detect the very small signals while maintaining the capacity to process very large inputs without causing components to saturate.

The prototype Cyberlink interface system functioned adequately with all the signal decoding performed by the host computer. However, decoding tasks are time sensitive and prevent the running of third party software with the Cyberlink interface software. A microprocessor incorporated into the bioamplifier was necessary to output a EEG/EMG/EOG data stream to the host computer.

An in-house electrical engineer was hired for this effort with the necessary expertise to address these and other challenges. Over a period of 16 months, the final preproduction prototype Bioamplifier/Analog-to-Digital-Converter/Microcontroller Interface Unit (the 'interface unit') was developed by B.A.T, Inc. and a subcontractor-manufacturer. It embodies a two-layer, pin-through-hole and surface mount printed circuit board, a 3.3 volt battery power supply with optical isolation and remote software control, durable plastic housing with low desktop 'profile', copper/silver spray shielding of housing interior to reduce electromagnetic susceptibility, a greatly reduced noise floor, increased signal resolution, and improved analog signal filtering characteristics (Figure 3).

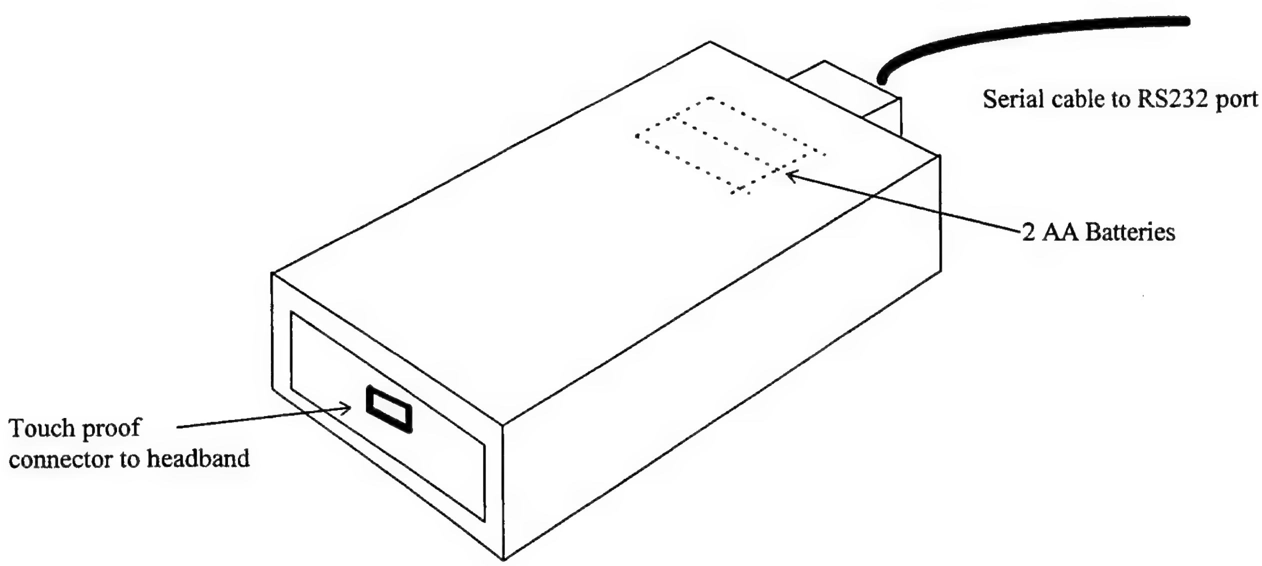

Figure 3. Interface Unit

The interface unit also has three separate channels for EEG, EOG, and EMG amplification, filtering, and processing, reverse voltage protection on the circuit board, microprocessor (PIC chip) conversion of signal data to an RS232 (serial) port-compatible bi-directional data string,

special connectors for 'daisy-chaining' with a second interface unit for two-player applications, a power supply adapter for either internal or external battery power, and full compliance with FCC Class B standards and European Community (CE) residential/light industrial standards for emissions and external susceptibility to high frequency radiation.

Interface Unit Specifications:

- Analog Gain: 500,000
- Noise At Front End: Less than 0.3 micro-volts
- Analog Bandwidth: 0.2 Hz to 3,000 Hz
- Analog to Digital Conversion: 6 Channels, 12 Bit Accuracy
- Power supply: 2 AA Batteries (included)
- Isolation: 2,500 Volts
- PC connection: RS232 serial port connection
- Dimensions: 190mm x 100mm x 40mm
- Weight: 13.5 oz.
- reverse voltage protection
- approved by the FCC and CE

4.0 SOFTWARE DEVELOPMENT UNDER SBIR PHASE II

4.1 The WINDOWS Visual C++ Server and Launcher

To use the Cyberlink successfully in operational settings, its forehead signal command data, converted into mouse and keyboard inputs, had to be made accessible to third party WINDOWS software applications running concurrently with any necessary Cyberlink control, adjustment, or display utilities. Tasking some of the signal conditioning and analysis to the microcontroller in the interface box was the first prerequisite to accomplishing this. Object-oriented code conversion and porting of the prototype Basic DOS programs to C++ and WINDOWS was the second.

First, a Visual C++ server program was created with a synthetic data object allowing testing and revision of the various signal decoding and control methods as the hardware was being perfected. This synthetic data object consisted of a sum-of-sine-waves file that approximated the expected signal output of the Cyberlink interface hardware. Next, an object-oriented EMG class divided into two units of functionality, the 'synthetic' and 'real' EMG events, was created.

A 'test server', a WINDOWS VBX, and Dynamic Link Libraries (DLL's) were constructed, documented and supplied to consultants to allow off-site development and testing of new WINDOWS training programs without the need for distributing the early versions of the hardware.

User interface software utilities were developed. A WINDOWS Cyberlink launcher program was designed to:

1) initiate a hardware-user interface continuity check which determined connection integrity at the Headband and RS232 port and displayed appropriate error boxes with corrective procedures to the user,

2) provide a continuous system integrity test alerting the user with an appropriate error box whenever the connection to the interface unit was disrupted or lost.

3) create a user log-in screen to provide an ID under which to store the user's interface formatting options, calibration and adjustment values in the server's INI files,

4) provide an expository graphical user interface with a composite Brainfinger, EEG, EMG and EOG display panel in clear and engaging graphics running in a window concurrently with other Cyberlink training applications to afford timely and intuitive user feedback for quick understanding and mastery of Cyberlink control (see Figure 4),

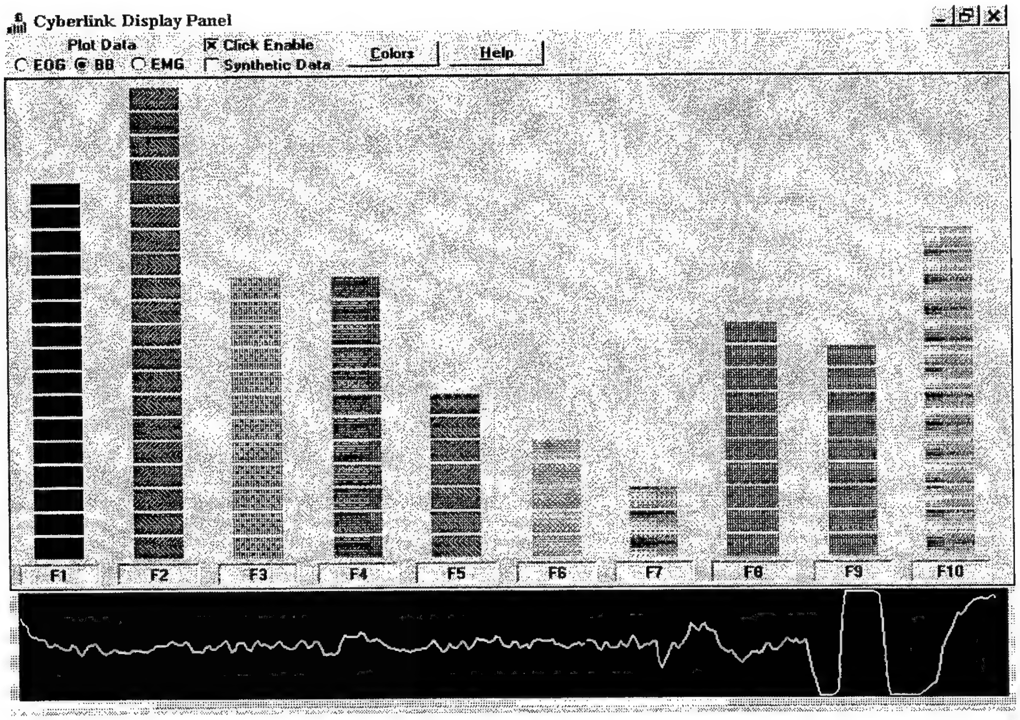

Figure 4: Cyberlink Signal WINDOWS "Display Panel"

5) provide an EMG-click practice program for click signal threshold/sensitivity adjustment and training with discrete facial gesture commands (see Figure 5),

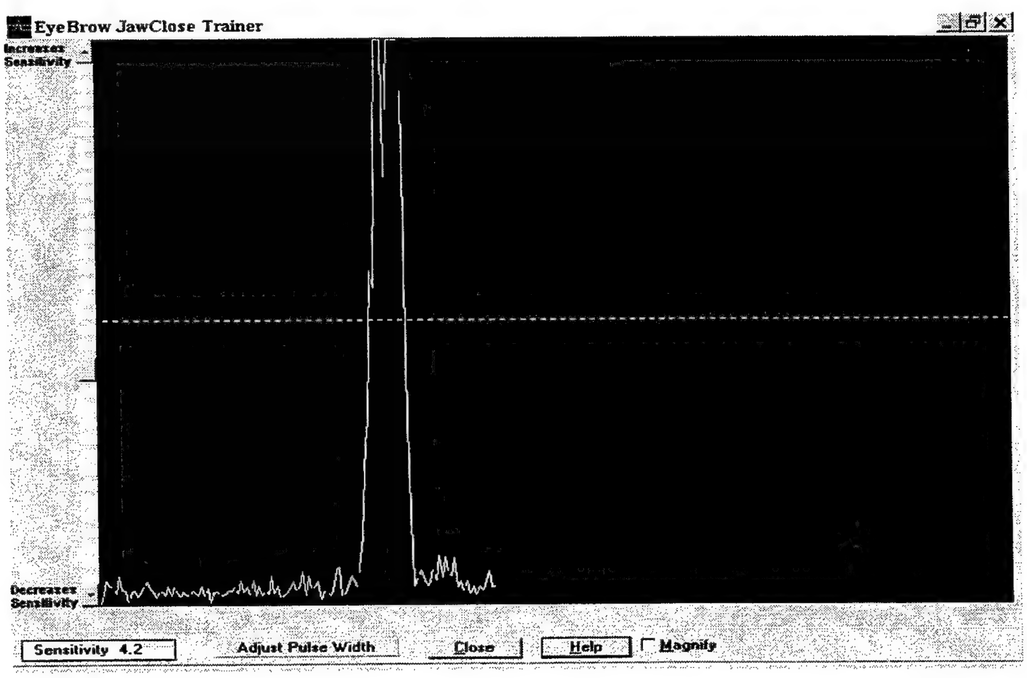

Figure 5: Cyberlink EMG Signal 'Click' Practice and Adjustment Utility

and 6) create a quick, easily accessed user interface self-adjustment program modeled after familiar WINDOWS joy stick or mouse adjustment routines (see Figure 6).

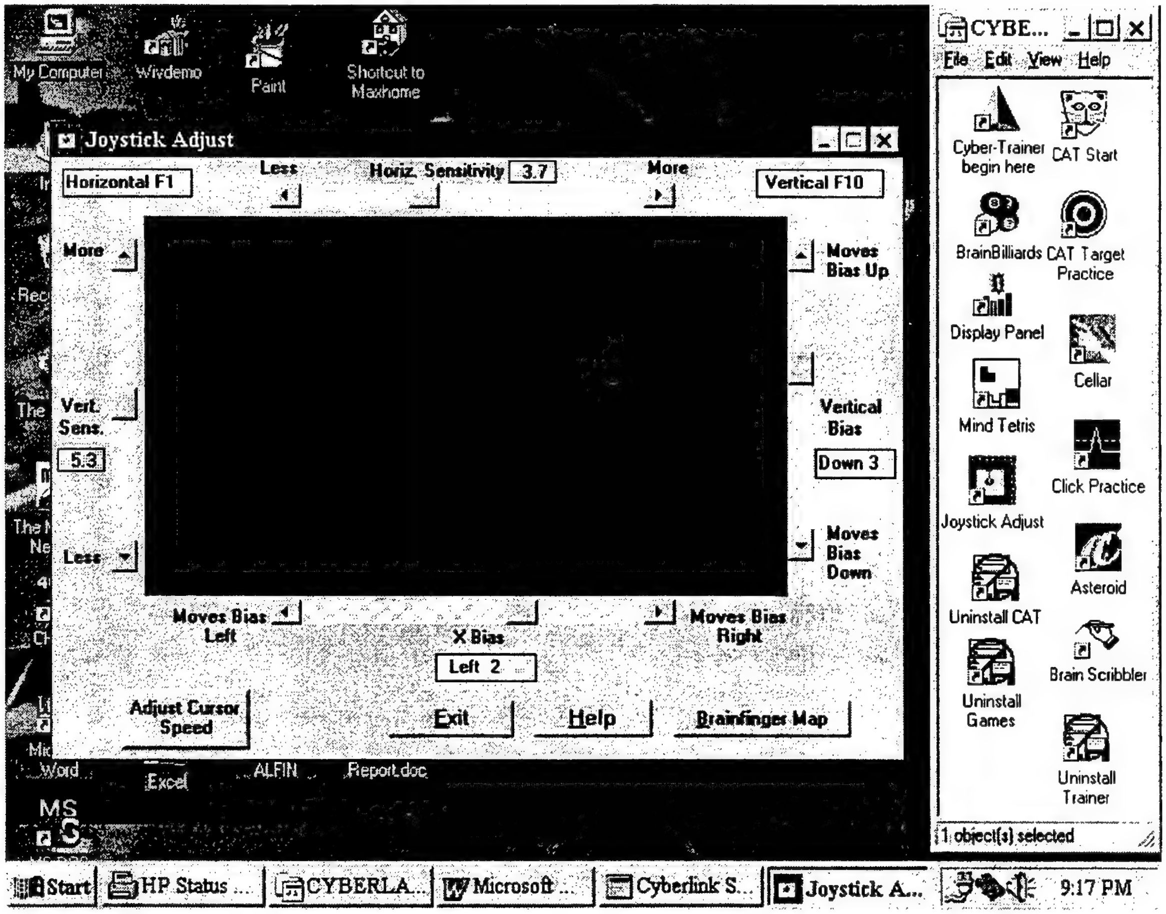

Figure 6: Cyberlink WINDOWS "Joystick Adjust" Utility

4.2 Development of User Calibration and Interface Adjustment

Calibration (Initial Adjustments)

Method One: *Brain Billiards* - The user adjustment interface employed in the Phase I SBIR experiments had encouraged the subjects to explore a previously untested range of cursor gain and offset adjustment settings with positive effects on task performance and efficiency. New tasks were developed for initial SBIR Phase II experiments to further explore this enlarged adjustment space and to provide data for the design of an improved user-interface calibration task in which performance error was converted (through a three-dimensional matrix) into optimal initial adjustment values.

These results culminated in the development of a WINDOWS application called "Brain Billiards". Brain Billiards combined a simple training task requiring sequential control of ten Brainfinger magnitudes (similar to "SlowBall" from the original DOS programs) with the calibration function (see Figure 7). This utility was added to the WINDOWS Cyberlink launcher program and subsequent tests demonstrated improved performance in two-axis control tasks among subjects whose initial interface adjustment values were established by the Brain Billiards matrix.

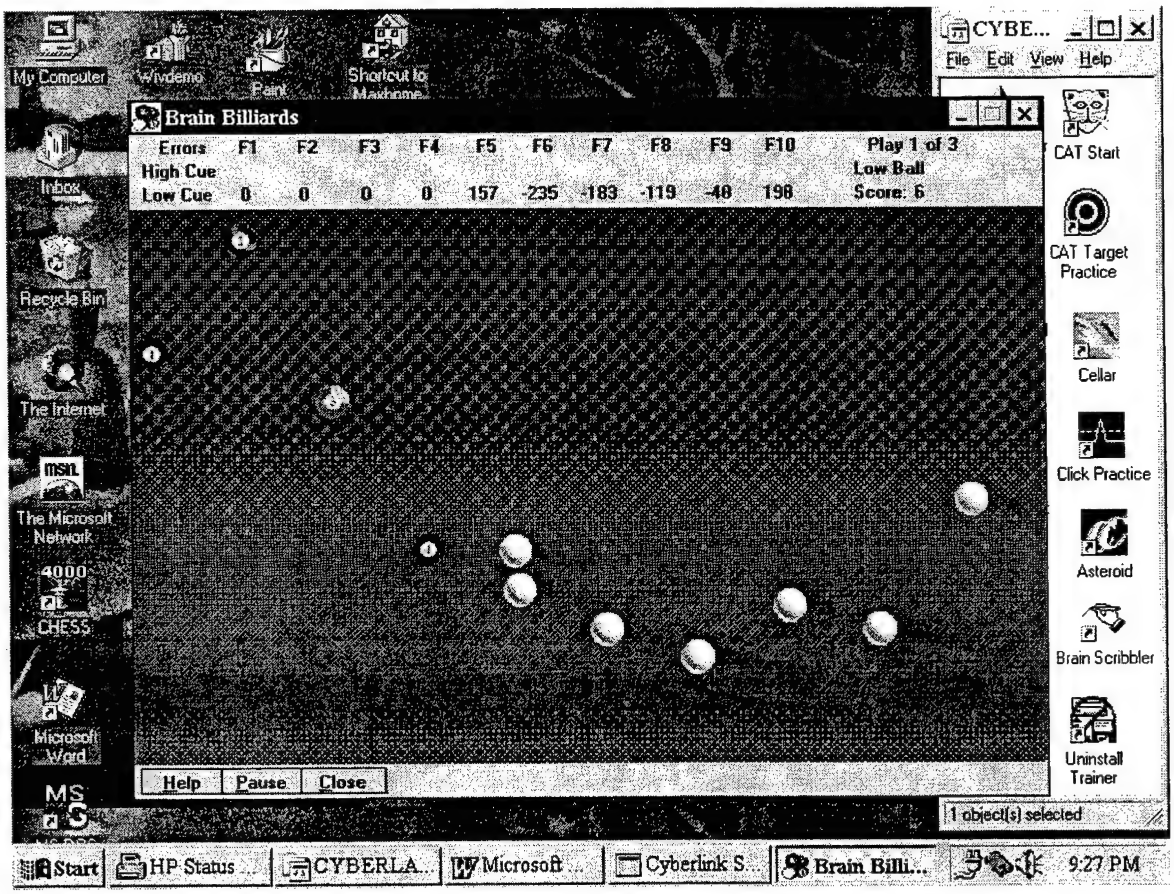

Figure 7: Cyberlink "Brain Billiards" Calibration Utility

Method Two: *Quick Start* Personality Type - Studies were conducted to verify anecdotal evidence indicating a strong correlation between personality type and ambient or baseline power in the BrainBody signal. Signal data and personality questionnaires were collected for 65 subjects (including 40 students at a local high school). Self-reported Type A personality operators (assertive, competitive, results-oriented) were found to have significantly higher baseline BrainBody signal levels than type B (low-key, cooperative, process-oriented).

A new initial gain and offset calibration program based on self-reported personality type was implemented. Subsequent evaluation with one and two-axis training applications indicated this method of determining initial user adjustments to be as effective as the higher resolution

adjustment matrix supplied by the Brain Billiards calibration task. It was added to the Launcher as an alternative calibration method called "Quick Start".

Automatic, On-Line Continuous Interface Adjustment

Experience-based revision of a continuous auto-adjustment routine continued throughout the software development phase. This behind-the-scenes program made continuous automatic corrections to the initial calibrations by adjusting the user-interface values effecting system gain and cursor offset for each Brainfinger. The auto-adjustments were based on sliding window averages of magnitude means and standard deviations for each Brainfinger.

Ultimately, with the improved functionality of both the interface hardware and the control paradigm, it was determined that little was gained with continuous auto-adjustment. Often cursor control was negatively affected and operators reported that they were working at cross purposes with the auto-adjustment routine as it continuously corrected and compensated for their intentional time-averaged control inputs as well as for unintentional input signal dynamics. Eventually, after several revisions failed to achieve the desired performance, the continuous auto-adjust approach was abandoned.

User-Selected Adjustments

Joystick Adjust: The joystick adjust utility was developed as an interactive display of Cyberlink two-axis control with click-and-drag scrollbars to implement user updates to the settings for gain and cursor offset. It was later refined to include separate control algorithm types, each providing different operational control characteristics (proportional, mono-velocity, velocity, etc.) from the same BrainBody signal source. A simple Brainfinger-to-axis-of-control mapping utility also was added to facilitate experiments with alternative configurations for this element of the control paradigm. As with the display panel and other utilities, joystick adjust could run concurrently with any other Cyberlink WINDOWS utility or application.

4.3 Initial System Integration and Documentation

After the calibration and adjustment programs became fully operational and were tested and refined, they were integrated into the launcher program. A proper syntax was designed and implemented in the launcher to: 1) register the user, 2) validate continuity of the sensors, interface unit to computer connection, and interface unit battery power status, 3) load the server, 4) launch the selected training applications with the appropriate user environment (i.e. user calibration, adjustment and format settings) if the user is previously registered with the launcher, or 5) launch the Brain Billiards (or Quick Start) calibration routine if the user had not previously registered with the launcher.

Integrated testing of the functionally stable interface hardware and server, the launcher programs, the control paradigm(s), and the first WINDOWS training programs with actual biological signals from the interface (as opposed to the computer-simulated signal from the test server)

became possible. Preliminary results of these initial system tests gave rise to some of the 'first generation' control paradigm design changes discussed in section 2.4 and also guided the evolution of the operational characteristics of the training programs.

Next an installation program for the WINDOWS server and launcher software, as well as the training/test applications, was created. Due to the increased complexity of programs running in the WINDOWS environment there was a need for special software to install the programs onto the computer. Attention was given to insure that correct versions of the VBX and DLL and various other program elements were copied to the appropriate locations in the operating system.

Due to the size of the software programs, an alternative to the floppy disk storage medium was developed and perfected so that the Cyberlink WINDOWS software could be ported from one computer to another via CD/ROM.

Integration of all system-level code (i.e. server, VBX, DLL, launcher utilities, etc.) into standard installation programs and testing with the training applications continued throughout the software development phase. The installation procedure for the system software modules and the training applications was updated and new install disks were prepared as the software continued to evolve.

Documentation

As a prerequisite to off-site beta-test release, software documentation in the form of on-line help screens and 'quick-tips' was added to the WINDOWS launcher and other Cyberlink applications.

In addition, a 50 page Cyberlink User Manual and a 12 minute tutorial video were written. This material was regularly revised and updated throughout the SBIR Phase II effort to keep it current with interface system hardware and software developments.

4.4 WINDOWS Training/Test Applications

Development of training and evaluation software continued throughout the latter half of the SBIR Phase II effort. Independent contractors were employed to design graphics, create graphics engines and develop new two-axis plus 'click' control test environments to more accurately model the full operational functionality of the WINDOWS mouse.

The most notable of the new training/test applications involved target acquisition by two-axis Brainfinger cursor positioning, 'click' selection and 'drag' by EMG spike inputs, and an EMG-spike target release over a receiving area. This application closely modeled the cursor functionality and control issues in the WINDOWS desktop environment and became very useful in providing data to inform and evaluate ongoing control paradigm developments.

A first-person, multi-media, three-dimensional maze application was also developed in which lateral cursor commands translated to rotation in the virtual environment and vertical commands

translated to forward and reverse motion. This application exposed many controller stability issues, eventually resulting in the development of several high stability control paradigms.

Further enhancement of the interface was done by adding the initial capability for two-user control in the WINDOWS environment and a new dual-player 'pong' training application was developed.

4.5 WINDOWS 3.1 Cyberlink Mouse Driver Prototype - "Hypermouse"

As the Cyberlink software matured, a parallel effort was begun to develop a WINDOWS Mouse driver allowing simultaneous cursor control of third-party WINDOWS software applications by a standard mouse and the Cyberlink controller. A device driver specialist was contracted from out-of-state as it was not possible to find a local consultant with the required expertise to develop software of this complexity. Shortly after his arrival at B.A.T., Inc, the consultant identified problems in the microprocessor protocol that needed to be corrected before driver implementation could be completed.

After three weeks of very intensive work, the consultant, working with B.A.T. personnel, completed the prototype WINDOWS 3.1 mouse driver. The driver, initially dubbed "Hypermouse", contained the necessary functionality to service, simultaneously, standard mouse inputs and decode two user-selected Brainfingers from the Cyberlink interface for x-y cursor control by issuing the appropriate mouse movement commands in accordance with the selected Cyberlink control paradigm. In addition, the driver computed the click events from the Cyberlink interface and performed the x/y/EMG auto-adjustment.

Due to the elegant, computationally inexpensive nature of the Cyberlink decoding process all of the driver capabilities could be accomplished with a driver that occupied less than 10 kilobytes of memory.

A Hypermouse parameter block was designed so that the user could selectively turn on Cyberlink driven mouse actions; some or all at the same time. For example, the user could elect to activate only the EMG-click or the cursor lateral control at one time. Preliminary tests with the Cyberlink EMG-click and the standard mouse x-y cursor control suggested this system combination might exhibit advantages in operational settings where short discrete response reaction times are critical.

A Hypermouse interface setup routine enabled the user to launch the Hypermouse with their necessary .ini file information (including interface formatting, adjustments and calibrations made in the WINDOWS Cyberlink launcher utilities) transferred to the Hypermouse parameter block. The user also selected which Cyberlink-driven mouse commands were to be active with the Hypermouse setup routine.

Preliminary tests of the Hypermouse x-y control indicated that the training applications and interface calibration/adjust routines were crucial to prepare the user prior to launching into the WINDOWS desktop environment with the Hypermouse. In this way, interface values optimizing

the user's cursor control were set in the Hypermouse parameter block. In the course of these tests, the value of the WINDOWS architecture and the Cyberlink training applications and other Cyberlink supporting software utilities became more fully appreciated.

4.6 First Integrated System Assessment

As the prototype driver; the headband and interface hardware; the user manual and other documentation; the server; the launcher formatting, adjustment, and training utilities; and the new training/test applications further matured they began to mesh together into a fully functional, integrated system ready for beta testing.

At this stage in the Cyberlink development effort, more information in the form of interface signal and task performance data, debriefing questionnaires, and anecdotal verbal feedback was essential for further progress. Throughout the latter half of the SBIR Phase II effort, extensive tests and focus studies with a large and varied subject population were conducted in-house; at assistive technology and computer electronics conventions, conferences, and trade shows; at local public schools and universities; and at beta sites in private homes and institutions all over the US, England, Europe, and Canada.

Overall, the results indicated that system and operator performance depended on four primary factors:

- **operational setting** - ambient room noise, distractions, and stressful influences affecting concentration; temperature conditions promoting excessive forehead sweat or the presence of oil-based makeup on the forehead that reduce the efficacy of the user's connection to and control of the interface; and other general environmental conditions.

- **operators' functional limitations** - users with traumatic brain injuries, Cerebral Palsy and other conditions limiting facial muscle functionality, sight impairments, autism, children under five years of age or others with attention deficit/hyperactivity disorder, and 'severe chronic skepticism' or a personal temperament reflecting an attitude of distrust of the novel and unfamiliar. All of above may limit ease of Cyberlink interface learning, calibration and use.

- **length of training** - Basic one-axis 'pong' and two-axis 'maze' control was often realized in the first 10 minutes of training. However, many users found that two-axis plus 'click' WINDOWS desktop-type applications required training of up to five or six 30-minute sessions before asymptotic performance was attained.

- **operator's ability to achieve independent signal control** - Approximately one out of five people tested exhibited an innate ability to raise selectively the signal input mapped to vertical cursor positioning without simultaneously and involuntarily raising their lateral input signal or unintentionally issuing an EMG-click command. Two out of five people tested showed that they could readily develop this crucial Cyberlink performance skill in the course of training by reducing the EMG or forehead muscle component of their vertical axis control

technique. The remaining two out of five appeared to be limited in their ability to develop sufficient signal independence within a practical training period (six 30-minute sessions) to achieve any substantial degree of two-axis plus click control

4.7 Second Generation Control Paradigm Development

The most successful control paradigm used in the first system assessment involved an EMG-spike discrete (click) command and velocity continuous cursor x-y positioning based on the time-averaged magnitudes of a delta and $beta_2$ Brainfinger, respectively. This paradigm, an extension of the original pre-SBIR II control model, came to be known as "The Classic" controller. The assessment results pointed to the need, and suggested an approach, for additional control paradigm development, testing, refinement, and finally integration into a "best-of" synthesis to create a universal interface - one able to be learned and applied by a majority of users in a broad range of operational settings and applications.

First, the following controller performance criteria set was developed:

1) *Separation* - degree of independence of x axis cursor control inputs from y axis cursor control inputs. Also, the degree of independence of y axis inputs from EMG-click commands.

2) *Stability* - degree to which the cursor retains its position in the absence of intentional continuous control inputs. Does it hover in the same basic area of the display or wander chaotically between control inputs?

3) *Accuracy (High Resolution)* - the degree to which small, volitional, easily executed inputs will reliably direct the cursor short distances to achieve intended positions and targets occupying small screen areas (i.e., < 32 x 32 pixels).

4) *Rapidity (Low Resolution)* - the degree to which larger, volitional, easily executed inputs will rapidly direct the cursor large distances to intended general screen areas (i.e., > 32 x 32 pixels) in a timely fashion.

5) *Learnability (Intuitiveness)* - the degree to which all of the above can be learned and achieved by the user after a minimum of explanation, adjustment and training.

Armed with the performance criteria, the system assessment data, and the earlier literature review and experimental data, a team of in-house and independent contractors worked on the problem of developing a second generation of control paradigm designs. Innovative solutions were encouraged. No idea was rejected on the basis of being too 'far-out.'

Within a few weeks, nearly a dozen new control paradigms were developed and, along with 'The Classic' controller, were subjected to evaluation. The most promising, those preferred by a significant percentage of the evaluators, are shown below with their grades in each of the performance criteria given on an ascending scale from one to five.

Evaluation of 'Second Generation' Control Paradigms

Paradigm	Design Elements	Evaluation: separation	accuracy	stability	rapidity	learnability	TOTAL
The Classic	1) X = 1.25 Hz, Y = 25.25 Hz 2) $power_1$ (time averaged magnitudes) 3) velocity (increases with ΔMag) 4) gain and cursor offset adjustments 5) stationary in motive signal null-zone 6) EMG, EOG, or selected Brainfinger spike activates 'mouse' click command	2 - 4	2 - 4	2 - 3	3 - 5	2 - 4	11 - 20 Comments: very user dependent (see section 4.6)
Etch-a-Sketch	1) X = 1.25 Hz, Y = 1.25 Hz (not simultaneous) 2) $power_1$ (time averaged magnitudes) 3) mono-velocity (fixed-speed threshold) 4) gain and cursor offset adjustments 5) stationary in null-zone and on inactive axis 6) EMG single click toggles active axis of motion; double-click is mouse click	5	3.5	4.5	3	3.5	19.5 Comments: very stable but click-intensive, fatiguing, "not elegant"
Tank Stick	1) X = $\frac{[\text{mag } 1.25 \text{ Hz}]}{[\text{mag } 25.25 \text{ Hz}]}$ Y = [mag 1.25 Hz] + [mag 25.25 Hz] 2) $power_1$ (time averaged magnitudes) 3) proportional 4) gain and cursor speed adjustments 5) stationary in null-zone 6) EMG spike 'mouse' click command	2	2 - 3	2	3	2 - 3	11 - 13 Comments: "fun to use," "not practical"
Flight Stick	1) X = $\frac{[\text{mag } 1.25 \text{ Hz}]}{[\text{mag } 25.5 \text{ Hz}]}$ Y = constant upward motion plus 'wrap' feature (cursor lowest vertical screen position follows highest) 2) $power_1$ (time averaged magnitudes) 3) proportional 4) gain and cursor speed adjustments 5) constant upward motion even when motive signal in null-zone 6) EMG spike 'mouse' click command	4	1.5	1.5	2.5	2	11.5 Comments: "fun to use," "not practical"

Two additional control paradigms were conceived during the second generation brainstorming, but were not implemented until the subsequent completion of the third party WINDOWS 95 Mouse driver:

1) *EOG Look Left/Right* - a lateral control method using the shape rather than the power of the motive signal to determine the direction of motion on the x axis. Based on a left-right phase reversal phenomenon observed in the EOG signal, corresponding to direction of lateral eye motion, a direction-specific horizontal axis control method was developed. A sharp leftward

glance initiates leftward cursor motion and a sharp rightward glance initiates rightward cursor motion. Cursor velocity is modulated by another aspect of the EOG waveform.

This method is still under evaluation at the time of this writing, although several beta sites have reported it to be their preferred x axis control method. Preliminary evaluation of the current embodiment indicates high grades in separation and stability but somewhat lower performance in areas of accuracy and rapidity.

Small targets are difficult to acquire without repeated passes on the lateral axis because the cursor is difficult to move short distances without 'overshooting'. Distant screen locations are difficult to attain in a timely fashion because the user must wait until the "ready" cue indicates the EOG waveform has returned to a state of stasis before further control inputs can be issued.

2) *The Cogitator* - an analysis of signal 'chaos' or time-averaged degree of variability, rather than power, for cursor vertical motion. The preliminary design, based on an in-house study of 35 Hz and 40 Hz gamma Brainfinger magnitudes over a fixed-period sliding sample window during the performance of Raven Progressive Matrices, shows promise but a more practical means of evoking the motive signal characteristic needs to be developed.

4.8 Building a Better Mouse: WINDOWS 95 Mouse Driver - C.A.T.

The WINDOWS 3.1 Hypermouse driver was an excellent proof-of-concept prototype and served as the development model for the more sophisticated WINDOWS 95 Cyberlink Mouse Driver with expanded capabilities.

A devise driver specialist was contracted to work on-site with the B.A.T., Inc. software development team responsible for the design and implementation of the second generation control paradigms. The new driver and support software was dubbed the "C.A.T.", Cyberlink Actuated Tracker. During the final stages of the SBIR II software development, the functionality was expanded to include:

- A C.A.T. monitor program to provide user discrete command feedback in the form of visual cues in the WINDOWS task bar and short WAV file auditory cues.

- A launcher/exit program affording access to an expanded parameter block to register the user with the appropriate interface adjustments and formatting; launch a C.A.T. set-up program in which the user selected the control paradigm and had access to a joystick-type x-y and discrete gesture adjustment and mapping routine; launch the selected WINDOWS 95 application; start the C.A.T. driver and accompanying C.A.T. monitor program; and provide a direct C.A.T. exit which simultaneously turned off the driver.

- A scanning option with EMG-click select for full hands-free navigation and control of the C.A.T. launcher/exit and setup routines.

To provide comprehensive mouse functionality, refinements were made to the EMG-click event and additional discrete gesture commands were created as more discriminating EMG waveform analysis algorithms were developed.

Since gestures provide more than button commands, the C.A.T. control functions were expanded to include a facial gesture activated cursor speed/resolution change. This toggle function integrated a low speed, high resolution mode and a high speed, low resolution mode into a single control paradigm, thus enhancing both accuracy and rapidity of performance.

To provide an easy method to temporarily deactivate the Cyberlink control of the mouse, restoring full control to the manual mouse without turning off the C.A.T. driver, a C.A.T. "sleep" mode was created. The additional discrete commands were default mapped to the expanded control functions but could be reformatted by the user.

C.A.T. Default Gesture Mapping

GESTURE	CHARACTER	ACTION(S)	MONITOR MESSAGE
1) Single Eyebrow Lift	Default = none user-selectable	Left Mouse Button Click & briefly stops cursor motion.	"Left Click"
2) Double Eyebrow Lift	"	Double Click & stops cursor	"Left Double Click"
3) Triple Eyebrow Lift	"	Click and Drag & stops cursor	"Left Drag"
4) Jaw Close	"	Switch Cursor Speed & Resolution	"Jaw Close"
5) Leftward Glance	"	Briefly stops cursor motion & when followed by Jaw Close toggles CAT "sleep/awake" mode	"Look Left"
6) Rightward Glance	"	Moves Cursor to Right	None (unless user-formatted with a discrete command Action)

A special suite of two-axis plus click control training applications was compiled under a Cyberlink program called "Trainer" to allow learning of Cyberlink control skills and interface formatting and adjustment in a less demanding environment prior to launching the C.A.T. in the more intense WINDOWS desktop. Adjustments and formatting made in the Trainer automatically carried over to the C.A.T. Programs.

Once fully operational, the C.A.T. driver and launcher/setup programs were added to the Cyberlink Install disks and were thoroughly tested in-house and shipped to all beta sites.

The final phases of the SBIR II effort comprised an exhaustive iterative process of beta testing, redesign, implementation, retesting, redesign and reimplementation.

During the final performance evaluation of the SBIR Phase II contract, a new control paradigm was designed and added to the C.A.T. and other Cyberlink programs:

EMG Vertical Control - a modification of The Classic controller, mapping EMG power to continuous vertical cursor velocity. Unintentional EMG-clicks are avoided because easily controlled, <u>very subtle</u> EMG inputs (well below the click threshold) reliably and accurately raise the cursor.

This development appears to improve The Classic's performance in all areas, particularly separation and accuracy. A synthesis of this paradigm with elements from several others provided the controller used in the final C.A.T. vs. Mouse comparative performance study.

5.0 FINAL CYBERLINK INTERFACE PERFORMANCE TEST: C.A.T. vs. MOUSE

5.1 Experimental Method

Subjects - three men and two women, ages ranging from 26 to 53 years, with a mean of 39.6 years, participated in the experiment. All reported normal or corrected-to-normal vision. Two had previous experience with the Cyberlink interface and three were naive. One subject was left-handed.

Materials - 1) Input device: Integrated Cyberlink hardware 'beta test' system, training and adjustment/formatting software utilities, and the WINDOWS 95 Cyberlink Mouse Driver - the C.A.T. (Cyberlink Actuated Tracker)

2) Input devices (sample of common manual mouse devices):
   a) *Dexxa* two button Mouse,
   b) *Logitech* three-button PS2 Mouse,
   c) *Toshiba Tecra* 'Touchstick' Mouse,
   d) *AST Ascentia A* 'Touchpad' Mouse

3) Performance Test Program: "Fitts Law" Target Acqusition Task

Experimental Design and Procedures - The experiment was designed to compare the performance of common manual mouse devices with the C.A.T. on a target acquisition and click-confirmation task. Independent variables were computer input device (one or more of four possible manual mouse devices, randomly balanced; or the C.A.T.), target size (16 x 16, 32 x 32, or 48 x 48 pixels) target distance (four possible on the vertical and five on the horizontal and diagonal axes), target direction angle (0, 45, 90, 135, 180, 225, 270, & 315 degrees as measured counter clockwise from 3 o'clock) and trial block. Subjects were trained as near to asymptotic performance as practical, given study time constraints, on each input device used in the experiment prior to running their experimental trials.

Each session consisted of six 'games' in a random sequence: one game with each of the three target sizes and two input devices (the C.A.T. plus one of the manual mouse devices). Note: some subjects performed additional three game sessions of the task with another of the manual-mouse devices to achieve balanced representation of each of these devices in the sample.

"Fitts Law" Target Acquisition Task - Each game consisted of 38 trials, one for each possible target location. Each target trial required the subject to move the cursor from the center of the screen to the target location and issue a left mouse button click command while within the boundaries of the target to confirm acquisition (Figure 8). The cursor then automatically returned to the green square in the center of the screen for two seconds after which the next target appeared.

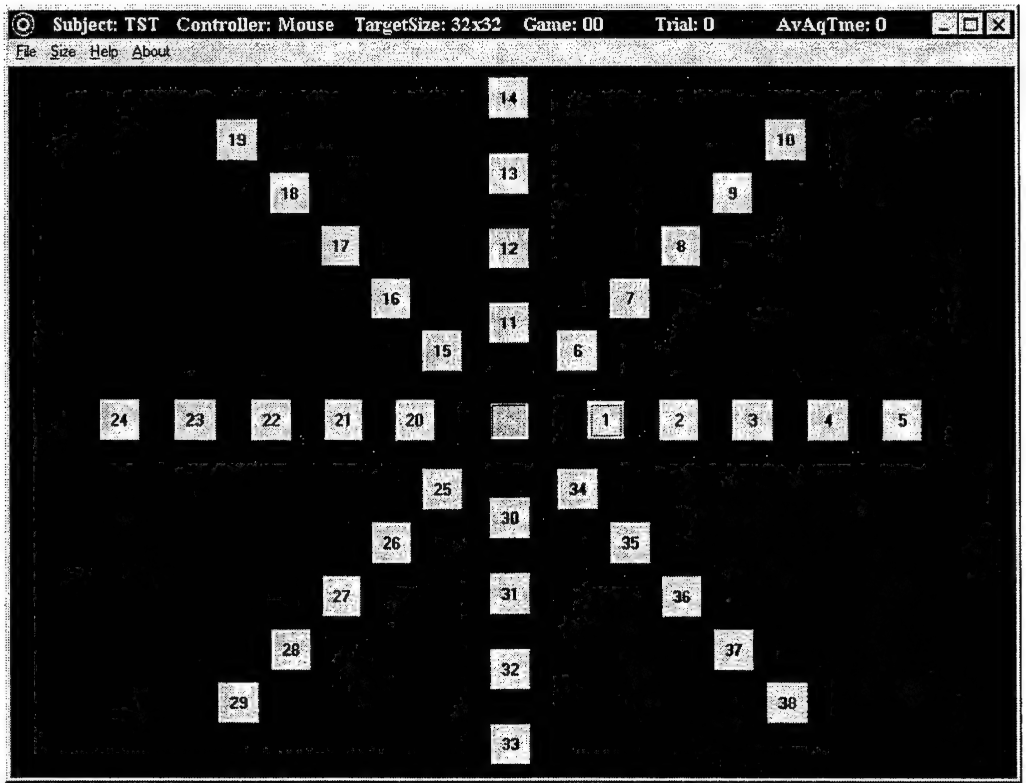

Figure 8. All Possible Target Locations in the Fitts Law Target Acquisition Task

The first target appearance was initiated by clicking within the center green box. The 38 targets appeared in a random order. The arrow cursor was replaced with crosshairs while within the target's boundaries. A programmed intermission was provided as a rest period after the appearance of the 19th target. Subjects were given no special coaching with regard to specific cursor control techniques.

The following data was automatically stored as a text file and imported into MS EXCEL for graphic display and analysis: 1) trial number (1 -38), 2) target acquisition time (in seconds), 3) Fitts Index of Difficulty or $\log_2$ [twice the target distance/target width], 4) target distance (in pixels), 5) target size (16, 32, or 48 pixels), 6) target angle (in degrees counterclockwise from 3 o'clock) 7) click commands off target, 8) time (in seconds) to first target contact with cursor, and 9) target number (1 -38).

5.2 Results

Paul M. Fitts derived the Fitts Law (Fitts, 1954) from Shannon's Theorem 17 of information transmission (Shannon and Weaver, 1949) to predict human movement times. Movement time (in this case, target acquisition time) is expected to increase proportionally with Index of Difficulty (*ID*) defined as

$$ID = \log_2 (2D/W)$$

where *D* is distance to target and *W* is target width.

This model has been applied successfully in several recent comparison performance studies of manual and alternative cursor control devices (i.e., Borah, 1995 and Epps, 1986).

The target acquisition time versus Fitts *ID* scatter plot of all trials using the C.A.T. input device (Figure 9) yields a relatively steep regression slope. This indicates a strong relationship between acquisition time and Fitts *ID* in good accord with Fitts Law. The targets with the highest Fitts *ID* values took more than twice as long, on average, to acquire as the targets with the lowest Fitts *ID* values.

The scatter plot of the data from the balanced sample of manual mouse devices shows a more shallow regression slope, yet one consistent with both the findings of other manual mouse studies (Borah, 1995 and Epps, 1986) and the predictions of Fitts Law.

Figure 10 shows the separate effects of target size, distance, and angle on acquisition time. With both the C.A.T. and the manual mouse devices, the smallest targets (16 x 16 pixels) are associated with a mean acquisition time disproportionately greater than those obtained with the two larger target sizes.

In the case of the manual mouse devices, this disparity does not present a practical problem for the user because average acquisition time for the 16 x 16 pixel target is less than two seconds. On the other hand, 16 x16 pixel mean acquisition time with the C.A.T. exceeds eight seconds. This suggests that the WINDOWS desktop minimum button sizes may need to be expanded (easily accomplished in the WINDOWS "control panel") for the C.A.T. to be an effective input device in operational settings.

The dependence of acquisition time on target distance (Figure 10) is slightly more pronounced with the C.A.T. than with the manual mouse, but the similarity of these results suggests that the C.A.T. may handle distances in a manner comparable to the manual mouse. Acquisition time appears to be slightly more influenced by target size (especially the 16 x 16 pixel target) than by target distance for the manual mouse, and perhaps also for the C.A.T.

Acquisition time is shown, in Figure 10 (bottom graph), to be less dependent on target angle than on the other factors except in the case of the 270° target trials with the C.A.T. These targets were directly below the cursor starting position and required only relaxation of the facial muscles (causing the cursor to drop) and very slight eye movements (to maintain lateral position) for the target to be intercepted. More active x-y control inputs were necessary for the other C.A.T. target angles.

The average interval between first cursor contact with the target boundary and confirmation of target acquisition (via EMG click with the C.A.T. and left mouse button with the manual devices) was approximately 20% of the total target acquisition time in both the C.A.T. and the manual mouse trials. This worked out to be approximately 1.3 seconds for the C.A.T. and .3 seconds for the manual mouse. The delay reflects a combination of target overshooting (less a factor with the manual mouse) and reaction time (less a factor with the C.A.T.).

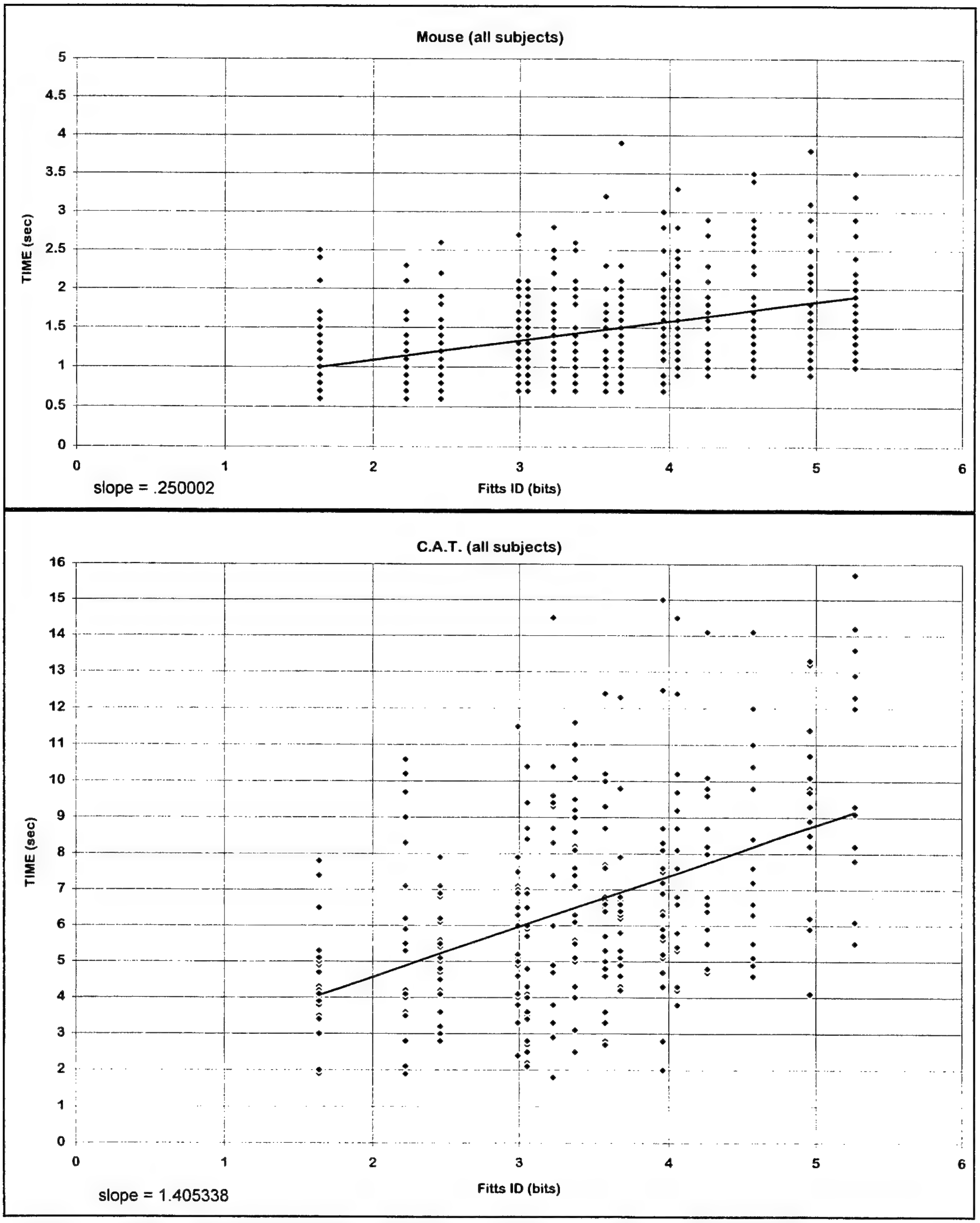

Figure 9. Target Acquisition Time Versus Fitts Index of Difficulty for Balanced Sample of Common Manual Mouse Devices and the Cyberlink Actuated Tracker (C.A.T.)

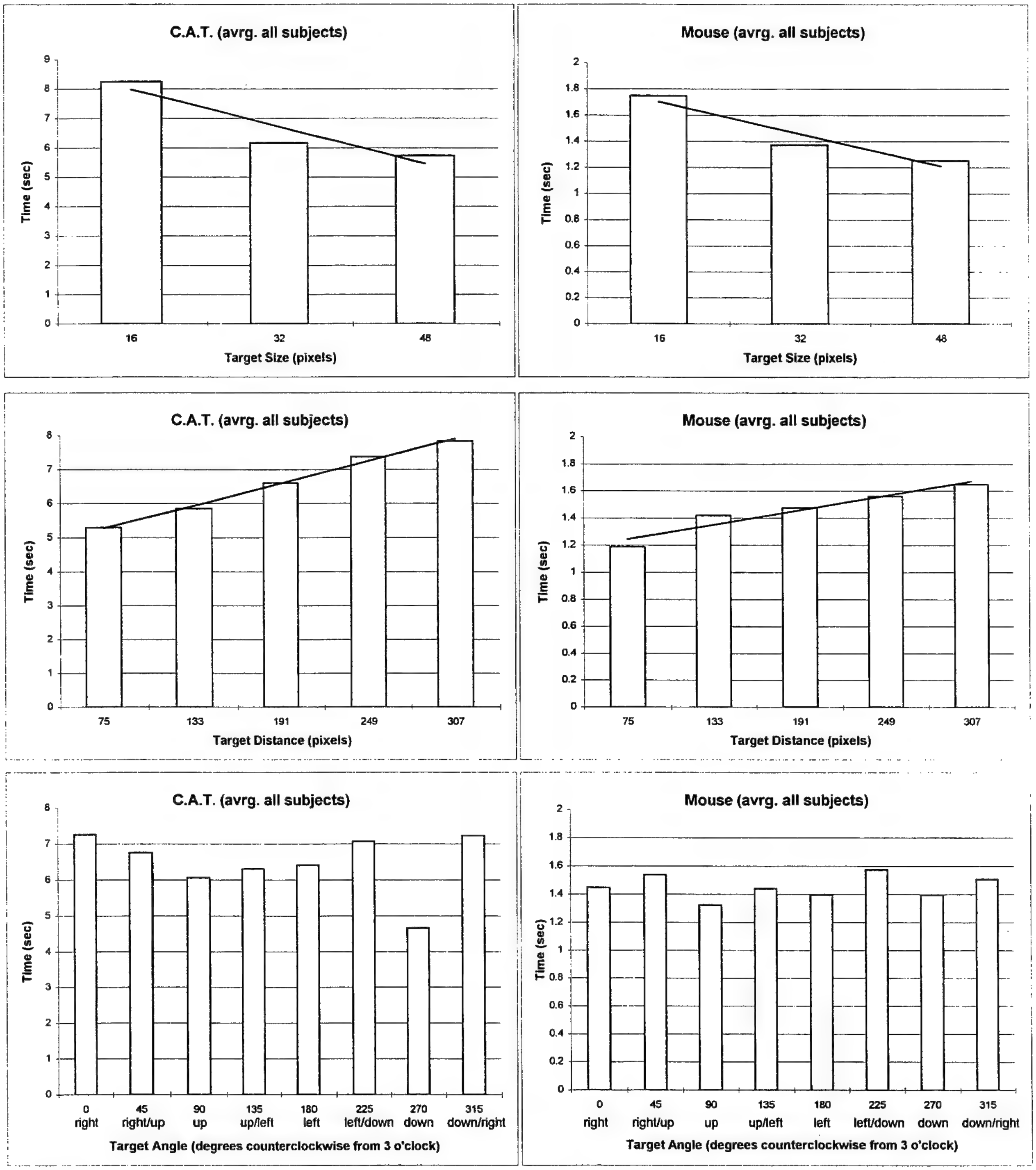

Figure 10. Factors Affecting Target Acquisition Time for Balanced Sample of Common Manual Mouse Devices and Cyberlink Actuated Tracker (C.A.T.)

5.3 Discussion

On average, the C.A.T. was approximately 4 times slower in the target acquisition task than the manual mouse. This difference is affected to some extent by the substantial manual mouse training advantage enjoyed by the subjects. All could claim a minimum of eight years PC computer mouse experience and no more than a few weeks experience with the C.A.T. controller used in this experiment.

Based on their training logs, it is likely that the naive users hadn't achieved full asymptotic performance with the C.A.T. and might have reduced their acquisition times by an additional 10 or 20% had a few more weeks been available for training.

Several subjects reported that, at first, the use of the Cyberlink interface in the task required more conscious effort than the manual mouse. Eventually, techniques and strategies, such as when to initiate C.A.T. cursor speed changes, began to feel more automatic and subconscious.

Further studies with longer training periods may shed additional light on the practical limits of Cyberlink interface speed, accuracy, and efficiency in time-intensive cursor positioning plus clicking tasks. Nevertheless, the results of this test would seem to indicate a very real potential for a viable alternative computer input device.

5.4 Conclusion

The findings of the Phase II effort have direct application to human-machine interaction. In addition to bringing the B.A.T. technology from proof-of-concept to preproduction prototype, the effort provided a new understanding of how humans interface with machines specifically through new control channels such as those obtained with the Cyberlink system.

In the military sector the Cyberlink interface could find its way into an aircraft cockpit as an alternative control input for non-critical flight systems such as avionics or radar displays to off-load some discrete manual control functions. At this time, Cyberlink x-y control does not appear to be rapid enough for the primary flight control environment.

On the other hand, the Cyberlink technology may provide a means to achieve limited aircraft control, not as a primary system but as an alternative or backup system. In the event a pilot was severely disabled due to injury or catastrophic failure, a system developed from the Cyberlink interface might provide the means by which the pilot could continue to control the aircraft or could liberate himself/herself from the aircraft.

Applications are ripe for development of the Cyberlink C.A.T. as a hands-free mobile computer interface in both the military and civilian sectors. It is particularly well suited for this application because its multiple discrete command functionality may augment or replace voice command inputs in noisy work environments.

In military and civilian sectors, the Cyberlink interface has great potential for assisting individuals who are severely disabled. It can provide hands-free assistive technology interfaces, environmental control, computer access, and recreation enabling an increased sense of independence and quality of life for individuals with limited motor control. It promises to be particularly well adapted to special needs word processing, hands-free WEB browsing and other internet applications, paving the way for revolutionary developments in facilitated communications.

In the field of education, the Cyberlink interface provides easy and rapid access to a wide range of biological signals for self discovery, research, relaxation/stress reduction, and group multi-media biofeedback events.

In the video game market, leading software developers and publishers perceive the B.A.T. technology as a possible means to extend the lifecycle of their current products by adding "thought control powers" and to increase the immersive/interactive characteristics of existing games. Others see the opportunity to expand their lines into a leading edge technology for personal, arcade, or other on-site entertainment centers.

6.0 REFERENCES

Achermann, P. & Borbely, A.A. (1987). Dynamics of EEG slow wave activity during physiological sleep and after the administration of benzdiazepine hypnoptics. *Human Neurobiology, 6*, 203-210.

Allen, W. E., Clement W. F., & Jex, H. R. (1970). *Research on display scanning, sampling, and reconstruction, using separate main and secondary tracking tasks* (NASA CR-1569).

Anderson, C., Stoltz, E. & Shamsunder, S. (1995a). Discriminating mental tasks using EEG represented by AR models. *Proceedings of the 1995 IEEE Engineering in Medicine and Biology Annual Conference, Sept., '95.*

Anderson, C., Devulapalli, S., & Stoltz, E. (1995b). EEG signal classification with different signal representations. In, Girosi, J., Makhoul, E., & Wilson, E. (eds.). *Neural Networks for Signal Processing V.* IEEE Service Center, Piscataway, NJ, pp. 475-483.

Anderson, C., Devulapalli, S., & Stoltz, E. (1995c). Determining mental state from EEG signals using neural networks. *Scientific Programming, Special Issue on Applications Analysis, 4, 3, Fall, '95*, 171-183.

Banquet, J.P. (1984), Spectral analysis of the EEG in meditation. Shapiro, D.H. & Walsh, R.N. (eds.), *Meditation: Classic and Contemporary Perspectives*. Adeline Publ. Co, New York, 493-501.

Barlow, J. S. (1983) Muscle spike artifact minimalization in EEGs by time-domain filtering. *Electroencephalography and Clinical Psychology, 55*, 487-491.

Bartlett, M. S., Makeig, S., Bell, A.J., Jung, T. & Senjowski, T. J. (1995). *Independent component analysis of EEG data. Society for Neuroscience Abstracts, v 21,* (in press).

Bartz, A. (1979). Percieved task complexity and reaction time on a single trial and a series of trials. *Journal of Motor Behavior, v 11, n 4,* 261-267.

Baumgartner, C. (1993). *Clinical Electrophysiology of the Somatosensory Cortex*, Springer-Verlag/Wein, N.Y., entire ref.

Berg, P. (1986). The residual after correcting event-related potentials for blink artifacts. *Psychophysiology, v 23, n* 3, 354-364.

Bergey, G. E., Squires, R. D. & Sipple, W. C. (1971). Electrocardiogram recording with pasteless electrodes. *IEEE Trans. Biomed. Eng., BME, 18*:206.

Besson, M. & Kutas, M. (1993). The many facets of repetition: A behavioral and electrophysiological analysis of repeating work in same versus different sentence contexts. *JEP:LMC 19(5):* 1115-1133.

Betts, R.P. & Brown, B.H. (1976). Methods for recording electrocardiograms with dry electrodes applied to unprepared skin. *Med. Biol. Eng., 14*:313.

Birbaumer, N., Lutzenberger, W. Rau, H., Mayer-Kress, G., Choi, I. & Braun, C. (1994). Perception of music and dimensional complexity in brain activity. *Intl. Journal of Bifurcations and Chaos.*

Bird, B. L., Newton, F. A., Sheer, D. E., & Ford, M. (1978) Biofeedback training of 40-hz in humans & Behavioral correlates of 40-hz biofeedback training in humans. *Biofeedback and Self-Regulation*, 3, 1-27.

Blanco, S., Garcia, H., Quiroga, R. Q., Romanelli, L., & Rosso, O. A. (1995). Stationarity of the EEG Series. *IEEE Engineering in Medicine and Biology,* July/August '95 395-399.

Borah, J. (1995). *Investigation of eye and head controlled cursor positioning technique,* (AL/CF-SR-1995-0018). Wright-Patterson Air Force, OH: Armstrong Laboratory.

Bourland, J.D., Geddes, L.A., Sewell, G., Baker, R., & Kruer, J. (1978). Active cables for use with dry electrodes for electrocardiography. *J. Electrocardiology, v11, n1*, 71-74.

Bullock, T. H. (1992). *Comparative analytical study of evoked and event related related potentials as correlates of cognitive processes* (AD-A261388; AFOSR-93-0043TR). Dept. of Neurosciences, California Univ., San Diego, CA.

Cazard, P. (1976). Interhemispheric synchrony of parietoocipital alpha rhythms during attention and cognition. *Transactions of L'Annee Psychologique (France) 74*, P7-20.

Carpenter, A. (1948) The rate of blinking during prolonged visual search. *Journal of Experimental Psychology, 38,* 587-591.

Chorlian, D. B., Porjesz, B. & Cohen, H. L. (1995). Measuring electrical activity of the brain: ERP mapping in alcohol research. *Alcohol Health & Research World, v 19, no. 4,* 315.

Cooper, R., McCallum, W.C. & Cornthwaite, S. P. (1989). Slow potential changes related to the velocity of target movement in a tracking task. *Electroencephalography and Clinical Neurophysiology*, 72, 232-239.

David, R.M., & Portnoy, W.M. (1972). Insulated electrocardiogram electrodes. *Med. Biol. Eng., 10:*742.

Davidson, R. J., & Schwartz, G. E. (1977). The influence of musical training on patterns of EEG asymmetry during musical and non-musical self generation tasks. *Psychophysiology, 14,* 58-63.

Deecke, L., & Grozinger, B. (1976) Voluntary finger movement in man: cerebral potentials and theory. *Biological Cybernetics,* 23, 99-119.

Deecke, L., Weinberg, H. & Brickett, P. (1982). Magnetic fields of the human brain accompanying voluntary movement: Bereitschaftsmagnetfeld. *Experimental Brain Research, 48,* 144-148.

De Oliveira, P. G., Queiroz, C. & Lopes De Silva, F. (1983). Spike detection based on a pattern recognition approach using a microcomputer. *Electroencephalography and Clinical Neurophysiology*, 56, 97-103.

De Toffol, B., Auret, A., Gaymard, B., & Degiovanni, E. (1992) Influence of lateral gaze on EEG spectral power. *Electroencephalography and Clinical Neurophysiology*, 82, 432-437.

Dorffner, G. (1995). Recognizing mental processes in EEG using neural networks: brain-computer interface research and the ANNDEE Project. Presented at *NIPS 95* (Neural Information Processing Systems Post-Conference Workshop, Dec.2, Vail, CO). Pre-print.

Drew, G. C. (1951)Variations in reflex blink-rate during visual motor tasks. *Quarterly Journal of Experimental Psychology, 3,* 75-88.

Dujardin, K., Derambure, P., Defebvre, L., Bourriez, J. L., Jacquesson, J. M., & Guieu, J. D. (1993) Evaluation of event-related desynchronization (ERD) during a recognition task. *Electroencephalography and Clinical Neurophysiology, 86,* 353-356.

Durnham, P. (1976). Distribution of practice as a factor affecting learning and/or performance. *Journal of Motor Behavior,* v 8, n 4, 305-307.

Elbert, T., Rockstroh, B., Lutzenburger, W., & Birmbauer, N. (eds.). (1984). *Self-Regulation of the Brain and Behavior*. Springer-Verlag Berlin Heidelberg.

Epps, B. (1986). Comparison of six cursor control devices based on Fitts' Law models. *Proceedings of the Human Factors Society-30th Annual Meeting-1986.*

Farah, M. J. (1984). The neurological basis of mental imagery: A componetial analysis. *Cognition, 18,* 245-272.

Farah, M. J., Gazzangia, M. S., Holtzman, J. D. & Kosslyn, S. M. (1985). A left hemisphere basis for visual imagery? *Neuropsychologica, 23,*115-118.

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neurophysiology. *Psychological Review, 95,* 307-317.

Flotzinger, D., Pfurtscheller, G., Neuper, C., Berger, H., Mohl, W. (1993). Classification of non-averaged data by learning vector quantitization and the impact of signal processing. *IEEE Engineering in Medicine and Biology, v 15 pt 1*, 263-264,

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology,*47, 381-391.

Ford, J. M., White, P. M., Lim, K.O. & Pfefferbaum, A. (1994). The relationship between P300 amplitude and regional gray matter volumes depends upon the attentional system engaged. *Enceph. & Clin. Neurophys., 90,* 214-228.

Fox, P. T., Fox, J. M., Raichle, M. E. & Burde, R. M. (1985). The role of cerebral cortex in the generation of voluntary saccades: a positron emission tomographic study. *Journal of Neurophysiology, v54, n 2,* 348-369.

Freeman, F. G. (1993). Brain wave correlates of attentional states: Event related potentials and quantitative EEG analysis during performance of cognitive and perceptual tasks. *NASA-ODU American Society for Engineering Education, 7-80,* 85-88.

Freeman, W.J.& Barrie, J.M. (1993). Spatio-temporal patterns of prepyriform, visual, auditory, and somesthetic EEG's in perception by trained rabbits. *Abstracts of the Society for Neuroscience, no. 504, v19*, 1229.

Freeman, W.J.& Barrie, J.M. (1994). Chaotic oscillations and the genesis of meaning in the cerebral cortex. Buzaski, G., et al., (eds.), *Temporal Coding in the Brain*, Springer-Verlag, 13-37.

Gabor, A.J. & Seyal, M. (1992). Automated interictal EEG spike detection using artificial neural networks. *Electroencephalography and Clinical Neurophysiology, 83,* 271-280.

Ganis, G., Kutas, M. & Sereno, M. (1996). The search for "common sense": An Electrophysiological study of the comprehension of words and pictures in reading. *Journal of Cognitive Neuroscience, v8, n2,* 89-106.

Gasser, T., Lothar, S. & Mocks, J. (1986). The correction of EOG artifacts by frequency dependent methods. *Psychophysiology, v 23, n 6,* 704-712.

Geddes, L.A., Moore, A.G., Baker, R.J., and Mack, R. 1976, An Easily Applied Dry Annular Dry Suction Electrode. J. Electrocardiol., 9:155.

Gevins, A. L., Yeager, C. L., Zeitlin, G.M., Ancoli, S. & Dedon, M. F. (1977). On-line computer rejection of EEG artifact. *Electroencephalography and Clinical Psychology, 42,* 267-274. *(Note: defines frequency bands of artifacts)*

Gevins, A. & Schaffer, R.E. (1980). *A critical review of electroencephalographic (eeg) correlates of higher cortical functions.* John, E.RR. (Ed.), CRC Critical Review in Bioengineering, 113-165.

Gevins, A., Bressler, S. L., Cutillo, B. A., Liles, J., Miller, J. C., Stern, J., & Jex, H. R. (1990). Effects of prolonged mental work on functional brain topography. *Electroenceph. & Clin. Neurophys.*, 76, 339-350.

Gevins, A., Filidei, M., Laidig, T., Leong, H. & Johnston, J. (1991). *Mental workload assesment in the cockpit: feasibility of using electrophysiological measures.* (TR-F49620-90-C-0077).

Gevins, A. S., Illes, J. (1991) Neurocognitive networks of the human brain. *Annals of the New York Academy of Sciences*, 620, 22-29.

Gevins, A. & Leong, H. M. (1992). *Physiological indices of mental workload Interim Technical Report* (AFOSR-93-0086TR). SAM Technology, Inc., San Francisco, CA.

Gevins, A., Leong H., & Smith, M. (1995) Problems and prospects for deriving a metric of mental workload from EEG measures. Presented at *NIPS 95* (Neural Information Processing Systems Post-Conference Workshop, Dec.2, Vail, CO). Pre-print.

Goldman, M.S. (1995). Recovery of cognitive functioning in alcoholics: the relationship to treatment. *Alcohol, Health, and Research World, v 19, n 2,* 148.

Gotman, J., Skuce, D.R., Thompson, C. J., Gloor, P., Ives, J. R., & Ray, W. (1973). Clinical applications of spectral analysis and extraction of features from electroencephalograms with slow waves in adult patients. *Electroencephalography and Clinical Neurophysiology, 35,* 225-235.

Gratton, G., Coles, M. G. H., Donchin, E. (1983) A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Psychology, 55*, 468-484.

Gratton, G., Coles, M. G. H., Donchin, E. (1984) A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Psychology, 55*, 468-484.

Grossman, W. I.& Weiner, H. (1966). Some factors affecting the reliability of surface electromyography. *Psychosomatic Medicine, 28,* 78-83.

Haxby, J. V., Grady, C. L., Duara, R., Schlageter, N., Berg, G. & Rapoport, S. I. (1986). Neocortical metabolic abnormalities precede non-memory cognitive defects in early Alzheimer's type dementia. *Archives of Neurology 43:*882-885.

Hart, S. G. & Staveland, L. E. (1988). Development of the NASA-TLX (Task Load Index): Results of experimental and theoretical research. Hancock, P. A., & Meshkati, N., (eds.), *Human Mental Workload.* Elsevier, p 89-120.

Harwin, et al. (1995). Design issues in rehabilitation robotics. (*See Page 9*) *IEEE Transactions on Rehabilitation Engineering, v3, n 1,* 5-11.

Heetderks, W. J. & Schwartz, A. B. (1995). Command-control signals from the neural activity of motor cortical cells: joy-stick control. *Proceedings of the 1995 Resna Research Symposium,,* 21-26.

Henriques, J. B. & Davidson, R. J. (1990) EEG activation asymmetries discriminate between depressed and control subjects. *SPR Abstracts, v 27, n 4,* 38-39.

Hjorth B. (1986). Physical aspects of EEG data as a basis for topographic mapping. In Duffy, F., (Ed.), *Topographic Mapping Of Brain Electrical Activity,* Butterworth Publs., Boston, MA, 175-182.

Hotz, R. L. (1996) . The brain: a work in progress. *L. A. Times, A-1.*

Inouye, T., Shinosaki, A., Iyama, A., & Matsumoto, Y. (1993) Localization of activated areas and directional EEG patterns during mental arithmetic. *Electroencephalography and Clinical Neurophysiology, 86,* 224-230

Issac, A. & Marks, D. F. (1994). Individual differences in mental imagery experience: developmental changes and specialization. *British Journal of Psychology, v85, n4,* 479-500.

Jagust, W. J., Reed, B.R., Martin, E.M., Eberling, J. L. & Nelson-Abbott, R. A. (1992). Cognitive function and regional cerebral blood flow in Parkinson's disease. *Brain, 115:* 521-537.

Jando, G., Siegel, R., Horvath, Z., & Buzsaki, G. (1992). Pattern Recognition of the EEG by artificial neural networks. *Electroencephalography and Clinical Neurophysiology, 86,* 100-109.

Jex, H.R., McDonnell, J.D. & Phatak, A.V. (1966). A "critical" tracking task for manual control research. *IEE Tansactions Of Human Factors In Electronics, Vol. HFE-7, No. 4, December 1966.*

Jex, H. R., Jewell, W. F. & Allen, R. W. (1972). Development of the dual-axis and cross-coupled crritical tasks. *Proc. of The Eight NASA-University Conference On Manual Control, May 1972.*

Jex, H. R., Magdaleno, R. E. & Junker, A. M. (1978). Roll tracking effects of g-vector tilt and various types of motion washout. *Proceedings of the Fourteenth Annual Conference on Manual Control, Univ. of Southern Calif. April 1978.*

Jobert, M., Escola, H., Poiseau, E. & Gaillard, P. (1994) Automatic analysis of sleep using two parameters based on principle component analysis of EEG spectral data. *Biological Cybernetics, 71,* 197-207.

Jokeit, H. & Makeig, S. (1994). Differing event-related patterns of gamma band power in brain waves of fast and slow reacting subjects. *Proceedings of the National Academy of Sciences, USA, 91:*6339-6343.

Johnson, J.P. and Allred, J.E. (1968). High impedance electrocardiograph amplifier-transmitter for use with dry electrodes. *Tech. Rep. SAM TR-68-55. Schl. Aerospace Med., Brooks AFB, Texas.*

Jung, T. P, & Makeig, S, (1994). Monitoring alertness dynamics via analysis of the EEG. *Proceedings of the Annual Symposium of the Biomedical Engineering Society,* 341-341.

Jung, T. P, & Makeig, S, (1995). Estimating level of alertness from the EEG. *IEEE Engineering in Medicine and Biology, (in press)* Proceedings: 1103-4.

Jung, T. P, & Makeig, S, (1995a). Estimating level of alertness from the EEG. *IEEE Engineering in Medicine and Biology, (in press)* Proceedings: 1103-4.

Jung, T. P, & Makeig, S, (1995b). Prediction failures in auditory detection from changes in the EEG spectrum. *IEEE Engineering in Medicine and Biology, (in press).*

Junker, A., Levison, W. H., & Gill, R.T. (1987) *A systems engineering based methodology for analyzing human electrocortical responses (*AAMRL-TR-87-030). Armstrong Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

Junker, A., Schnurer, J. H., Ingle, D. F., & Downey, C. W. (1988). *Loop-closure of the visual-cortical response* (AARML-TR-88-014). Armstrong Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

Junker, A., Berg C., Schneider, P., Terenzio, M., O'Conner, P., & McMillan, G. (1995). *Effects of training and individual differences on performance with the Cyberlink alternative control interface* (AL/CF-TR-1995-0109). Wright-Patterson Air Force Base, OH: Armstrong Laboratory.

Junker, A., Berg C., Schneider, P., & McMillan, G. (1995). *Evaluation of the Cyberlink interface as an alternative human operator controller* (AL/CF-TR-1995-0011). Wright-Patterson Air Force Base, OH: Armstrong Laboratory.

Kasamatsu, A. & Hiri, T. (1984). An electroencephalographic study of the zen meditation. Shapiro, D.H. & Walsh, R.N. (eds.), *Meditation: Classic and Contemporary Perspectives.* Adeline Publ. Co, New York, p. 480-492

Kaufman, L. (1993). *Cognition and the brain: A continuation of the university research initiative at New York University* (AD-A271872; AFOSR-93-0818TR). New York University, NY.

Keele, S. W. (1986). Motor control. Boff, K., R., Kaufman, L. & Thomas J. P., (eds.), *Handbook of Perception and Human Performance. Vol. II: Sensory Processes and Perception,* John Wiley ans Sons, p 30 - 60.

Klorman, R. (1991). Cognitive event-related potentials in attention deficit disorder. *Journal of Learning Disabilities v 24, n 3,* 130-140.

Kutas, M. & Hillard, S. A. (1980) Reading senseless sentences: Brain potentials reflect semantic incogruity. *Science, 207:*203-205.

Kutas, M., Hillard, S. A. & Gazzanigia, M. S. (1988). Processing of semantic anomaly by right and left hemispheres of commissurotomy patients: Evidence from event-related potentials. *Brain, 111:*553-576.

Kutas, M. & Van Petten, C. (1990). Electrophysiological perspectives on comprehending written language. In New Trends and Advanced Techniques in Clinical Neurophysiology, *Electroenceph. and Clin. Neurophys (suppl. 41),* 155-167.

Lancaster, J. L., Fox, P. T., Davis, G. & Mikiten, S. (1994). BrainMap: A database of human functional brain mapping. *Proceedings of the Fifth International Conference: Peace Through Mind/Brain Science.*

Larkin, L.I. (1985). A fuzzy logic control for aircraft flight control. Sugeno, M. (Ed.), *Industrial Applications of Fuzzy Control,* North Holland, Amsterdam.

Laszio, J. & Livesey, J. P. (1977). Task complexity, accuracy, and reaction time. *Journal of Motor Behavior, v 9, n 2,* 171-177.

Linden, M., Habib, T., & Radojevic, V. (1991) A controlled study of EEG biofeedback effects on the cognitive disorders and learning disabilities. *Developmental Medicine and Child Neurology.*

Linden, M., Habib, T., & Radojevic, V. (1996) A controlled study of the effects of EEG biofeedback on cognition and behavior of children with attention deficit disorder and learning disabilities. *Biofeedback and Self Reg., 21,* 35-49.

Lindsley, D.B. (1952). Psychological phenomena and the electroencephalogram. *Electroenceph. Clin. Neurophysiol. 4*, 443-456.

Lubar, J. O. (1989). Encephalographic biofeedback and neurologic applications. Basmajan, V. (ed.), *Biofeedback. Principles and Practice for Clinicians*, Williams and Wilkins, Baltimore, Maryland, 67-90.

Lubar, J. O., & Lubar, J. F. (1989) EEG biofeedback of SMR and beta for treatment of attention deficit disorders in a clinical setting. *Biofeedback and Self-Regulation, v 9, p 1,* 1-23.

Luders, H.O., Lesser, R. P., Dinner, D. S., Morris, H. H., Wyllie, E., Godoy, J. & Hahn, J. H. (1992). A negative motor response elicited by electrical stimulation of the human frontal cortex. *Advances in Neurology, 57,* 149 -157.

Makeig, S., Elliott, F. S., Inlow, M. & Kobus, D. (1990). *Predicting lapses in vigilance using brain evoked responces to irrelevant auditory probes.* TR 90-39, Naval Health Research Center, San Diego, CA.

Makeig, S. & Inlow, M. (1992). Lapses in alertness: coherence of fluctuations in performance and EEG spectrum. *Electroencephalography and Clinical Neurophysiology, 86,* 23-35.

Makeig, S. & Jung, T. P. (1995). Tonic, phasic, and transient EEG correlates of auditory awareness in drowsiness. *Cognitive Brain Research* (downloaded copy off Net.).

Marks, D. F., Uemura, K., Tatsuno, J. & Imamura, Y. (1985). EEG topographical analysis of imagery. McGaugh (Ed.), *Contemporary Psychology: Biological Processes and Theoretical Issues,* Amsterdam: Elsevier, 211-223.

Marks, D. F. & Isaac, A. R. (1995). Topographical distribution of EEG activity accompanying visual and motor imagery in vivid and non-vivid imagers; electroencephalographic activity; Imagery and Motor Processes. *British Journal of Psychology, v 86, n 2,* 271.

Mast, J. & Victor, J. (1991). Fluctuations of steady-state VEP's: interaction of driven evoked potentials. *Electroencephalography and Clinical Neurophysiology,* 78, 389-401.

Matousek, M. & Petersen, I. (1983). A method for assessing alertness fluctuations from EEG spectra. *Electroencephalography and Clinical Neurophysiology, 55,* 108-113.

McMillan, G. (1995). EEG-based control utilizing self-regulation of the steady-state visual evoked response (SSVER). *NIPS*95 Workshop Abstracts.*

McMillan, G. R., Calhoun, G.L., Middendorf, M. S., Schnurer, J. H., Ingle, D. F., & Nasman, V. T. (1995). Direct brain interface utilizing self-regulation of the steady-state visual evoked response. *Proceedings of the RESNA 18th Annual Conference* (Vancouver, Canada), pp. 693-695.

McRuer, D.T. & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEE Transactions On Human Factors In Electronics, Vol. HFE 8,* 231-249.

McRuer, D.T. (1980). Human dynamics in man-machine systems. *Automatica, v16, n 3,* 237-253.

Miller, E. B. (1996). Music therapy & biofeedback. *Expressive Therapy Concepts.*

Montgomery, R. W., Montgomery, L. D. & Guisado, R. (1992). Cortical localization of cognitive function by regression of performance on event-related potentials. *Aviation, Space, and Environmental Medicine, v63, n 10,* 919-924.

Moore-Ede, M., Campbell, S. & Baker, T. (1989). Effect of reduced operator alertnness on the night shift on process control operstor performance. *Advances in Instrumentation, Proceedings v44 p 3,* 967-970.

Munk, M. H. J., Rolfsema, P. R., Pieter, R, Konig, P., Engel, A. K., & Singer, W. (1996). Role of reticular activation in the modulation of intracortical synchronization. *Science, v 272, n 5259,* 271.

Nakajima, I. (1995). FFT analysis of masseter muscle during reaction to a warning signal. *Electromyography and Clinical Neuralphysiology, 35,* 281-284.

Nakamura, M., Shibasaki, H., Imajoh, K., Nishida, S., Neshige, R. & Ikeda, A. (1992). Automatic EEG interpretation: a new computer-assisted system for the automatic integrative interpretation of awake backround EEG. *Electroencephalography and Clinical Neurophysiology, 82,* 423-431.

Nelson, W. T., Hettinger, L. J., Cunningham, J. A., Roe, M. M., Hass, M. W., Dennis, L. B., Pick, H. L., Junker, A., & Berg, C. (1996a). Brain-body-actuated control: assessment of an alternative control technology for virtual environments. *Proceedings of the 1996 IMAGE CONFERENCE,* 225-232.

Nelson, W. T., Hettinger, L. J., Cunningham, J. A., Roe, M. M., Hass, M. W. & Dennis, L. B. (1996b). Navigating through virtual flight environments using brain-body-actuated control. *Proceedings of the IEEE Virtual Reality Annual International Symposium (March 1997).*

Oscar-Berman, M. & Hutner, N. (1993). Frontal lobe changes after chronic alcohol ingestion. Hunt, W. A. & Nixon, S. J., (eds.), *Alcohol-Induced Brain Damage.* NIH Publication No. 93-3549, p 89-120.

Othmer S., Othmer S, & Marks C. S. (1991). EEG biofeedback training for attention deficit disorder, specific learning disabilities, and associated conduct problems. *EEG Spectrum White Paper, www.eegspectrum.com.*

Paller, K.A, & Kutas, M. (1992). Brain potentials during memory retrieval provide neurophysiological support for the distinction between conscious recollection and priming. *Journal of Cognitive Neuroscience, 4:* 375-391.

Passingham, R. (1995). *The frontal lobes and voluntary action,* Oxford University Press.

Peltoranta, M. & Pfurtscheller, G. (1994). Neural network based classification of non-averaged event-related EEG responses. *Medical and Biological Engineering & Computing, 32,* 189-196.

Pfurtscheller, G & Berghold, A. (1989). Patterns of cortical activation during planning of voluntary movement. *Electroencephalography and Clinical Neurophysiology,* 72, 250-258.

Pfurtscheller, G & Pregenzer, M. (1995). Recognizing mental processes in EEG using neural networks: brain-computer interface research and the ANNDEE project. *Proceedings of the 1995 IEEE Enineering in Medicine and Biology Annual Conference, Sept., '95.*

Poline, J. B. & Mazoyer, B. M. (1994). Analysis of individual brain activation maps using a hierarchical description and multiscale detection. *IEEE Transactions v 13, n 3,* 704-710.

Pope, A. T. & Bogart, E. H. (1994). *Method of encouraging attention by correlating video game difficulty with attention level* (NASA-CASE-LAR-15022-1). NASA, Langley Research Center, Hampton, VA.

Porjesz, B. & Begleiter, H. (1995). Event-related potentials and cognitive function in alcoholism. *Alcohol, Health, and Research World, v 19, n 2,* 108.

Potter, A. & Menke, L. (1970). Capacitive-type of bio-medical electrode. *IEEE Trans. Biomed. Eng., BME-17*:350.

Poulton, E. C. (1974). *Tracking skill and manual control*, New York: Academic Press.

Prutchi, Sagi-Dolev (1993). In-flight biolectrodes. *Aviation, Space and Environmental Medicine*, 552-556.

Qu, H. & Gotman, J. (1993). Improvement in seizure detection performance bt automatic adaption to the EEG of each patient. *Electroenceph. and Clin. Neurophys.*, *86*, 79-87.

Rippon, G. (1990). Correlation between electrodermal and electroencephalographic activity: Hand and hemisphere. Pieter, J. D., Drenth, J. A., Sergeant, R. J. (eds.), *European Perspectives in Psychology, Vol. 2.*, John Wiley and Sons, 425-442.

Roessgen, M., Boasash, B., & Deriche, M. (1993). Preprocessing noisy EEG data using time-frequency peak filtering. *IEEE Engineering in Medicine and Biology, v15, p1,* 465-466.

Schwartz, M. (1987). *Biofeedback: A practitioners guide.* Guilford Press, NY.

Searight, H. R., Nahlik, J. E., & Campbell, D. C. (1995) Attention-deficit/hyperactivity disorder: assessment, diagnosis, and management. *Journal of Family Practice, v 40, n 3,* 270.

Shannon, C. E. & Weaver, W. (1949). *The Mathematical Theory of Communication,* University of Illinois Press, Urbana, IL.

Shcheblanova, Y. I. (1984). On the EEG indices of the complexity of thought processes: Changes in EEG activation during the solution of Raven's problems of varying complexity. *Novye Issledovaniya v Psikhologii, v 30(1),* 5-9.

Shepard, R. N. & Podgorny, P. (1978). Cognitive processes that resemble perceptual processes. Estes, W. K. (ed.), *Handbook of Learning and Cognitive Processes, Vol. 5*, Erlbaum, Hillsdale, NJ.

Shimamura, A. P., Jernigan, T. L. & Squire, A. (1988). Radiological (CT) findings and neurophysiological correlates. *Journal of Neuroscience, 8:*4400-4410.

Short, P.L. (1953). The objective study of mental imagery. *British Journal of Psychology, 44,* 38-51.

Sobotka, S.S., Davidson, R. J., & Senulis, J. A. (1992) Anterior brain electrical asymmetries in response to reward and punishment. *Electroencephalography and Clinical Neurophysiology, 83,* 236-247.

Speil, G. (1987). Is there a possibility of differentiating between children with minimal cerebral dysfunction by means of computer-assisted automatic EEG analysis? *Advances in Biological Psychiatry, 16,* 171-177.

Steriade, M. (1996). Arousal: revisiting the reticular activating system. *Science, v 272 n.5259,* 225.

Sterman, M. B., Mann, C. A., Eriksen, H. R., Olff, M. & Ursin, H. (1992). Encephalographic correlates of psychological defense. *Proceedings of the Human Factors Society, 36th Annual Meeting, v 1,* 76-80.

Sterman, M. B., Kaiser, D. A., Mann, C. A., Suyenobu, B. Y., Beyma, D. C., & Francis, J. R. (1993). Application of quantitative EEG analysis to workload assesement in an advanced aircraft simulator. *Proceedings of the Human Factors and Ergonomics Society, 37th Annual Meeting, v 1,* 12-54.

Sumathy, S. & Krishnan, C. N. (1991). Automatic machine classification of patient anaesthesia levels using EEG signals. *IECON Proceedings v 3*, 2349-2351.

Taheri, B. A. (1995). An active, microfabricated, scalp electrode array for EEG recording. *Proceedings of the NIPS*95 Workshop.*

Takano, N., Maruyama, T., Tamagawa, M. & Yana, K. (1993) EOG artifact cancelling for EEG analysis using RLS adaptive filtering technique. *IEEE Engineering in Medicine and Biology, v* 15 pl, 348-349.

Ulrich, R. & Miller, J. (1994). Effects of truncation on reaction time analysis. *Journal of Experimental Psychology: General, v 123, n 1*, 34-80.

Uemura, K., Ryu, H., Shioura< A. &Yokota, N. (1983). EEG topographic system for clinical study of higher functional localization. *Proceedings of the Australasian Winter Conference on Brain Research, Queenstown, New Zealand.*

Verleger, R. (1993). Valid identification of blink artefacts: are they larger than 50uV in EEG records? *Electroencephalography and Clinical Neurophysiology,* 87, 354-363.

Veselis, R. A. (1993). Analytical methods to differentiate similar EEG spectra: neural network and discriminant analysis. *Journal of Clinical Monitoring v 9 n 4,* 257-267.

Walpow, J. R., et al. (1991). An EEG-based brain-computer interface for cursor control. *Electroenceph. and Clin. Neurophys., 78:* 252-259.

Weiss, T., Beyer, L., Hansen, E., Rost, R. & Paproth, A. (1987). Motor imagination: Dynamic of some neuropysiological correlates. *Neuroscience, 22,* 511.

Williams, J. D., Rippon, G., Stone, B. M. & Annett, J. (1995). Psychophysiological correlates of dynamic imagery. *British journal of Psychology, v 86, n 2,* 283.

Williams, W., Zaveri, H.P., & Sackellares, J. C. (1995).Time frequency analysis of electrophysiology signals in epilepsy. *IEEE Engineering in Medicine and Biology, v 27,* 133-143.

Wisko, J. Jr., Gevins, A. & Williamson, S. J. (1992). *The AFOSR workshop on the future of EEG and MEG* (AD-A264338; AFOSR-93-0256TR). EEG Systems Lab, San Fransisco, CA .

Wilson, G. (1994). Topographical analysis of cortical evoked activity during a variable demand processing task. *Aviation, Space, and Environmental Medicine, v 65, n 5,* A54-A61.

Wong, P. K. H. (1991). *Introduction to Brain Topograhpy*, Plenum Press, N.Y., 1-15, 72-84.

Yoshitake, H. (1978). Three characteristic patterns of subjective fatigue symptoms. *Ergonomics, 21,* 231-233.

Zheng, C., Williams, W. & Sackellares, J. C (1993). RID time-frequency analysis of median filter and lowpass filter in reducing EMG artifacts in EEG recording. *IEEE Engineering in Medicine and Biology, v 15, p 1,* 350-351.